

# **TECHNOLOGICAL RESEARCH AND DEVELOPMENT AUTHORITY (TRDA)**

**FINAL SUMMARY REPORT: NASA NO. NCC10-0010**

**"SUPERSONIC GAS-LIQUID CLEANING SYSTEM"  
RESEARCH PROJECT**

**TECHNOLOGICAL RESEARCH AND DEVELOPMENT AUTHORITY  
STATE OF FLORIDA  
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TITUSVILLE, FLORIDA 32780**

**FINAL SUMMARY REPORT**

**under**

**NASA COOPERATIVE AGREEMENT NO.: NCC10-0010**

**entitled**

**“Supersonic Gas-Liquid Cleaning System”  
Research Project**

**Principal Investigator:**  
**Report Period:**

**Frank Kinney**  
**09/12/94 - 09/11/95**

**February, 1996**

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## **I. INTRODUCTION**

The *Supersonic Gas-Liquid Cleaning System Research Project* consisted mainly of a feasibility study - including theoretical and engineering analysis - of a proof-of-concept prototype of this particular cleaning system developed by NASA-KSC. The cleaning system utilizes gas-liquid supersonic nozzles to generate high impingement velocities at the surface of the device to be cleaned. The cleaning fluid being accelerated to these high velocities may consist of any solvent or liquid, including water. Compressed air or any inert gas is used to provide the conveying medium for the liquid, as well as substantially reduce the total amount of liquid needed to perform adequate surface cleaning and cleanliness verification. This type of aqueous cleaning system is considered to be an excellent way of conducting cleaning and cleanliness verification operations as replacements for the use of CFC 113 which must be discontinued by 1995.

To utilize this particular cleaning system in various cleaning applications for both the Space Program and the commercial market, it is essential that the cleaning system, especially the supersonic nozzle, be characterized for such applications. This characterization consisted of performing theoretical and engineering analysis, identifying desirable modifications/extensions to the basic concept, evaluating effects of variations in operating parameters, and optimizing hardware design for specific applications.

Under a partnership arrangement, TRDA, NASA-KSC, Bethune-Cookman College, Embry-Riddle Aeronautical University, and Precision Fabricating and Cleaning, working as a team, provided the research and technology necessary for the further design and development of an operational cleaning system based on the supersonic nozzle concept for cleaning and verification of cleanliness. As a commercial partner, PFC plans to utilize this research and technology to possibly adapt this cleaning concept for other potential markets.

## **II. TRDA PARTNERSHIP TASKS**

As per Cooperative Agreement No. NCC10-0010, the tasks to be performed by TRDA are listed below, along with a brief narrative of activities undertaken by TRDA to satisfy our partnership responsibilities. Descriptions provided below are for activities subsequent to those documented in the project Performance Report, submitted in January, 1995.

### **(1) Provide co-funding (in-kind contributions) of the project.**

TRDA staff spent considerable time and effort managing and coordinating project activities. Contributions attributed to the project were in excess of \$15,400.

- (2) **Provide the necessary manpower for proper implementation, and business and technical management of the overall project.**

Frank Kinney (TRDA Executive Director) served as Project Director; Matthew La Vigne (TRDA Contract Manager) served as Project Manager, and Libbie Strickland (TRDA Executive Secretary) provided the required secretarial support. The resumes of Kinney and La Vigne were provided with the project proposal to NASA. TRDA also utilized qualified consultants for technical support on the project.

- (3) **Contract with Bethune-Cookman College (B-CC) to provide the required technical assistance from qualified engineering students, and to assist the TRDA in regard to contracting with E-RAU for fluid mechanics experts and managing certain administrative functions, as needed.**

The contracting process and roles of each partner were described in the Performance Report.

- (4) **Serve as the main interface and point of contact for all of the project partners.**

TRDA served as the central point of contact for all partners relative to the project, while encouraging direct contact and working relationship between all the partners. TRDA scheduled and hosted monthly meetings of all partners to discuss project activities and review schedules, as well as to provide an open forum to consider project obstacles encountered and overall direction of the project.

TRDA also held many informal meetings with individual partners, acting as an intermediary on numerous occasions to facilitate working relationships between project participants.

- (5) **Conduct quarterly progress reviews of the work performed by B-CC and E-RAU in conducting the research.**

Although promising only quarterly progress reviews of the work performed by project partners, TRDA has taken an even more aggressive position in overseeing project activities. By contract, TRDA *required monthly written progress reports from each partner*, in addition to a monthly meeting.

Monthly reports received since the submission of the Performance Report from each project partner are included in this report as Attachment "A". These reports give an update on project activities from January through March, 1995.

**(6) Track all performance schedules and insure adherence thereto.**

Project schedule information was included in the Performance Report and is touched on in the Final Reports contained within this report.

**(7) Provide best efforts in insuring the protection of the partners' proprietary data and intellectual property rights.**

As with all TRDA partnership projects, continued to exercise its best efforts to insure the appropriate protection of proprietary data and intellectual property rights of the partners.

**(8) Acquire and submit reports and other documentation regarding the overall project.**

TRDA submitted a Performance Report in January of 1995, and hereby submits a Final Summary Report. Activities and findings of the entire project are described in great detail in the Final Project Reports from each of the three cooperating research partners; Bethune-Cookman College, Embry-Riddle Aeronautical University, and Precision Fabricating and Cleaning, Inc. These Final Project Reports are included in this report as Attachment "C".

**(9) Prepare and submit the required invoices to NASA-KSC, and maintain adequate files and records in connection the cooperative agreement and other activities regarding the partnership.**

TRDA submitted the appropriate Federal Cash Transaction Reports to NASA-KSC for to cover associated costs of the project. A summary outlining the expenditure of funds can be found in Attachment "B" of this report. The project expended \$16,101.54 less than originally budgeted, and TRDA requested that NASA-KSC de-obligate these funds from the project.

TRDA maintains a complete file of project related documents, activities, etc. relevant to the Supersonic Gas-Liquid Cleaning System. This file is open to NASA-KSC inspection at any time.

### **III. ATTACHMENTS**

**"A" - Progress Reports**

**"B" - Final Project Budget Summary**

**"C" - Final Project Reports**

**ATTACHMENT “A”**

**Supersonic Gas-Liquid Cleaning System Research Project  
Monthly Progress Reports**

# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## MONTHLY PROGRESS REPORT

January 12, 1995

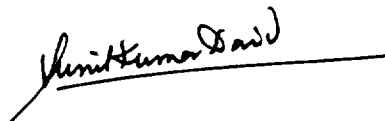
This project report is submitted by Dr. Sunil K. David to Bethune Cookman College, and describes work performed during the fourth month of the research project (Ref: TRDA Grant #411).

During this month of Dantec 55M01 main unit with cover plate and 55M10 Standard Bridge was received at KSC/NASA from the LaRC/NASA. According to the work plan mentioned in earlier reports, this instrument is to be set at a convenient place for the velocity measurement required to verify the theoretical model. Considering various factors PF&C, cocoa was chosen for the site for experiment. Mr Tom Jezowski set all the necessary facility for the Nozzle and the control panel in a mobile cleaning lab at PF&C which helped considerably in setting the experiments.

With SGLCS in operation, following task were carried out while:

1. Anemometer required a probe to measure supersonic velocity of air and air-water mix (Gas-Liquid mix) stream coming out of the nozzle. A wedge-shaped hot-film probe (Dantec probe 55R31) was selected and procured from Denmark on urgent basis to save the time.
2. Probe was mounted as per prescribed procedure on a calibrated linear bench. Preliminary experiments were performed to put CTA and the Probe in operation.
3. A procedure was evolved to align the probe, nozzle and the direction of stream in a straight line for all the positions of the probe on the linear bench.
4. Experiments were performed to measure the velocity of the air-stream at various distances from the exit-plane of the nozzle for back pressures 200, 300, 400, and 500 PSIG. Consistency and the reproducibility of the results were also checked.
5. Observations under the same conditions will be taken for air-water mixtures to investigate the physical effects of the water droplets (or ice dust) in the system..

To calibrate the probe either a known flow source is required or a conical pitot will be required.





# **SUPERSONIC GAS-LIQUID CLEANING SYSTEM PROJECT**

## **MONTHLY PROGRESS REPORT**

**February 10, 1995**

This project report is submitted by Dr. Sunil K. David to Bethune Cookman College, and describes work performed during the fifth month of the research project (Ref: TRDA Grant #411).

A meeting was arranged with Dr. James M. Meyers<sup>1,2</sup> and his colleagues at NASA/Langley Research Center, Hampton (Virginia) to discuss methods for particle sizing and flow measurement using Laser Doppler Anemometry and the availability of the equipment facilities. This visit explored the possibility of using unique facilities at Langley and/ otherwise to find other economical methods to collect data required for the project<sup>3</sup>. Dr. Meyers and his colleague Dr. William M. Humphreys, Jr. have kindly agreed to provide their non-intrusive 'Laser Transit Anemometry' facility to collect required data on velocity and particle size distribution.

Experiments were also conducted for several days in the mobile cleaning lab at PF&C, Cocoa to measure velocity of the supersonic flow of two phase fluid of the nozzle. As mentioned in earlier reports and brief notes, pitot probe is to be used as one of the methods to obtain velocity data along the axis of the fluid stream of the supersonic nozzle. There are several advantages of using pitot probe for supersonic flow measurements<sup>4</sup>. Somehow, a pitot probe for the supersonic flows was not available easily, therefore, it was decided to make one. A pitot probe was designed at B-CC and tested at PF&C. This probe was used to measure static pressure (after the shock) along the axis of the nozzle stream. Readings were taken for the breathing air and also for the mixture of breathing air and water at different settings of pressures and axial distances.

Few optical arrangements<sup>5</sup> were also tried this month to get visual images of the supersonic flow of the stream of the breathing air and also air-water mixture. Finally, after several trials and experimental adjustments clear images of the flows were obtained on the screen. Photographs of these images were taken for each setting. Equipment from B-CC labs were used for this purpose.

1. Performance Test of Laser Velocimeter System for the Langley 16-Foot Transonic Tunnel,
1. James F. Meyers, et al; NASA technical Paper 2502 /AVSCOM Technical Report 85-B-4, December 1985.
2. The Elusive Third Component, J.F. Meyers; International Symposium on Laser Anemometry, Ed: A. Dybbs and P.A. Pfund, Nov. 1985.
3. Brief note sent to Dr. Meyers regarding the nozzle project and the definition of required data (enclosed)
4. 'Pitot tube as a calibration device for turbulence measurement', Sadek Z. Kassab; Rev. Sci. Instrum. 61(6), 1757-9 (1990)
5. 'High Speed Wind Tunnel Testing', Alan Pope and Kenneth L. Goin; pp229 ; Robert E. Krieger Publi. NY 1978.

One of the tasks given to the students working on this project, is to arrange and compile the technical literature and subsequently prepare a bibliography of the experimental work which will go in the final technical report of this project. This work is now in progress and will be finished soon<sup>6</sup>.

Arrangements are made to conduct phase three experiments<sup>7</sup> at NASA/Langley research center, Hampton, during Feb. 21-24, 1995.

6. Students working on this project could not start their work before the Spring session of 1995 due to their earlier commitments for other courses in Fall semester schedule of 1994.

7. 'Schedule of the experimentation, a note submitted in Nov.94.

Muzim Kumar Said

# LITERATURE SURVEY

Following Journals and Technical Literature were scanned to search relevant information (direct/ indirect) which may help in selecting appropriate method(s) and adopting most suitable experimental procedure(s) to be used in the project, to measure velocity and particle size distribution in the stream of supersonic flow of breathing air and also of breathing air mixed with 0.01% of water, coming out from the proto-type nozzle.

- [A] Review of Scientific Instruments
- [B] Applied Optics
- [C] AIAA Journal
- [D] Measurement Science and Technology
- [E] Books and Conference Proceedings
- [F] Technical Information from the Instrument manufacturers
- [G] Technical Reports, Press Release and others

[A] REV. OF SCIENTIFIC INSTRUMENTS, Vols. 54 - 64, 1983 - 93 + current issues.

44.60 Thermodynamic processes (phenomenology, experimental techniques)

Ring wire anemometer—Part I: Calibrations and cooling laws. - Jean-Paul Giovanangeli, Pierre Chambaud, and Patrice Mestayer; 58 (11), 2172-4 (1987)

Ring wire anemometer—Part II: Measurement of small scale turbulence. - Patrice Mestayer, Jean-Paul Giovanangeli, and Pierre Chambaud; 58 (11), 2175-80 (1987)

47.27 Turbulent flows, convection, and heat transfer

Density measurements of a pulsed supersonic gas jet using nuclear scattering. - J. G. Pronko, D. Kohler, I.v. Chapman, T.T. Bardin, P.C. Filbert, and J. D. Hawley; 64(10), 2947-51.

47.40.K Supersonic and hypersonic flows

Comparison between constant-current and constant-temperature hot-wire anemometers in high-speed flows. - D. Bestion, J. Gaviglio, and J. P. Bonnet; 54 (11), 1513-24(1983)

02-13-95 12:05  
Velocity distribution of supersonic nozzle beams. - H. Haberland, U. Buck, and M. Tolle; **56**(9), 1712-6 (1985)

#### **47.55.E Nozzles**

Velocity distribution of supersonic nozzle beams. - H. Haberland, U. Buck, and M. Tolle; **56** (9), 1712-6 (1985)

Experimental study of a hot wire, sonic nozzle probe for concentration measurements  
Damien Maroteaux, Fadia Maroteaux, and Michel Murat; **62** (4), 1057-62 (1991)

#### **47.60 Flows in ducts, channels, and conduits**

Velocity visualization in gas flows using laser-induced phosphorescence of biacetyl.  
- B. Hiller, R. A. Booman, C. Hassa, and R. K. Hanson; **55** (12), 1964-7 (1984)

Curved-tube flowmeter. - H. Joutman; **56** (12), 2295-8 (1985)

Aeroacoustic flow sensor. - P. Shakkattai, E. Y. Kwack, and L. H. Back; **62** (9), 2205-12 (1991)

#### **47.80 Instrumentation for fluid dynamics**

Comparison between constant-current and constant-temperature hot-wire anemometers in high speed flows. - D. Bestion, J. Gaviglio, and J. P. Bonnet; **54** (11), 1513-24 (1983)

Calibration of a three-element hot-wire anemometer. - G. T. Skinner and W. J. Rae; **55** (4), 578-81 (1984)

Laser Doppler velocimeter for multicomponent measurement using an electro-optical modulator demonstrated for a two-component optical configuration. - R. H. Bahnen and K. H. Koeller; **55** (7), 1090-3 (1984)

Particle discrimination and background suppression in photon-correlation laser velocimetry. - Todd D. Fansler; **55** (10), 1556-63 (1984)

Velocity visualization in gas flows using laser-induced phosphorescence of biacetyl. - B. Hiller, R. A. Booman, C. Hassa, and R. K. Hanson; **55** (12), 1964-7 (1984)

Laser Doppler velocimetry using polarization-preserving optical fibers for simultaneous measurement of multidimensional velocity components. - Noboru Nakatani, Muneo Tokita, Takao Izumi, and Tomoharu Yamada; **56** (11), 2025-9 (1985)

Ring wire anemometer—Part I: Calibrations and cooling laws. - Jean-Paul Giovanangeli, Pierre Chambaud, and Patrice Mestayer; **58** (11), 2172-4 (1987)

Ring wire anemometer—Part II: Measurement of small-scale turbulence. - Patrice Mestayer, Jean-Paul Giovanangeli, and Pierre Chambaud; **58** (11), 2175-80 (1987)

Dedicated microprocessor system to control laser Doppler velocimetry measurements and to reduce data. - D.V. Srikantaiah, T. Philip, and W. W. Wilson; **59** (5), 793-6 (1988)

Signal generator for stimulation of laser doppler velocimetry experiments. - J. C. Amare and M.A. Robolledo; **60** (5), 939-42 (1989)

Determination of the magnitudes and signs of flow parameters by hot-wire anemometry. Part I. Measurements using hot-wire X probes. - Michael Acrivlellis; **60** (7), 1281-5 (1989)

Determination of the magnitudes and signs of flow parameters by hot-wire anemometry. Part II. Measurements using a triple hot-wire probe. - Michael Acrivlellis; **60** (7), 1281-5 (1989)

Pilot tube as a calibration device for turbulence measurement. - Sadek Z. Kassab; **61**(6), 1757-9 (L) (1990)

Experimental study of a hot wire, sonic nozzle probe for concentration measurements. - damien Maroteaus, Fadila Maroteaux, and Michel Murat; **62** (4), 1057-62 (1991)

A fast-response microthermocouple. - P. Beckman, R. P. Roy, K. Whitfield, and A. Hasan; **64** (10), 2947-51 (1993)

## **[B] APPLIED OPTICS, Vols. 11 - 32 + current issues:**

Measurement of Particle size, Number Density, and Velocity Using a Laser Interferometer. W. M. Farmer; **11**(1), 2603-12 (1972)

Sample space for particle size and velocity measuring interferometers. W. M. Farmer; **15**, 1984-89 (1976)

Two optical methods for simultaneous measurement of particle size, velocity, and refractive index. Amir Naqwi, Franz Durst, and Xiaozhi Lui; **30**, 4949-59 (1991)

Analysis of laser light scattering interferometric devices for in-line diagnostics of moving particles. Amir A. Naqwi and Franz Durst; **32**, 4003-18 (1993)

**[C] AIAA JOURNAL Vol. 20 - 30, 1983 - 1994 + current issues**

Comparison of Hot-Film Probe and Optical Techniques for Sensing Shock Motion.  
Fredric W. Roos and Thomas J. Bogar; **20**, 1071-76 (1982)

Semi Conductor Laser Doppler Anemometer for Application in Aerodynamic Research.  
Franz Durst, Reiner Muller, and Amir A Naqwi; **30**, 1033-38 (1992)

**[D] Measurement Science and Technology Vol 1 - 3 + current issues**

Asensitive optical receiver with application to a visible laser diode anemometer. M.  
R. Mackenzie, A. K. Tieu, L. N. Binh, and P. B. Kosasih - **3**(1992) 685-686

A fast-response catalytic hot wire sonic nozzle probe to measure fuel concentration  
in a fuel/air mixture. C. F. Li, M. Murat, J. Jullien, and M. J. Zhu - **5**(1994) 151-156

A fully compensated hot/cold wire anemometer system for unsteady flow velocity and  
temperature measurements. K. Bremhorst and L. J. W. Graham - **1** (1990) 425-30.

**[E] BOOKS & CONFERENCE PROCEEDINGS:**

'High-Speed Wind Tunnel Testing' Alan Pope and Kenneth L. Goin; Robert E. Krieger  
Publishing Company, New York 1978.

'Fundamentals of Hot-wire Anemometry' Charles G. Lomas; Cambridge University  
Press, Cambridge 1986.

'Thermo & Laser Anemometry' A. F. Ployakov ;1989.

'Principles and Practice of Laser-Doppler Anemometry' Second Edition: F. Durst, A.  
Melling and J.H. Whitelaw; Academic Press; New York 1981.

'Proceeding of International symposium on Laser anemometry' Editors: A. Dybbs &  
P.A. Pfund; The American society of Mechanical Engineers, 1985.

'Photon Correlation and Light Beaming Spectroscopy' Editors: H.Z. Cumins and E.R.  
Pike; Plenum, New York, 1977.

'Photon Correlation Spectroscopy and Velocitometry' Editors: H.Z. Cummins and E.R.  
Pike, Plenum, New York, 1977.

'Photoelectric Statistics'; Springer, Berlin 1978.

'Measurement of suspended particles by Quasielastic light scattering'; Siley, New York 1983.

'Photon Correlation Techniques in Fluid Mechanics'; Editor: E.O. Schulz-Dubois, Springer, New York, 1983.

#### **[F] TECHNICAL DATA /INFORMATION FROM THE MANUFACTURERS:**

'Laser Doppler Anemometry and determination of particle size by a relaxation-length method an TNM' D. Olejak, W. Heiser, D. Reisinger and S. Wagner;  
Dantec Information No. 11, June 1992; Dantec Meas. Techn. A/S.

'Pressure Atomiser PDA asurements'; C. J. Bates  
Dantec Information No. 11, June 1992; Dantec Meas. Techn. A/S.

'The Enhanced Burst Spectrum Analyzer'; Chris Caspersen;  
Dantec Information No. 11, June 1992; Dantec Meas. Techn. A/S.

'Spectrum analysis of LDA Signals'; L. Lading;  
Dantec Information No. 5, September 1987; Dantec Meas. Techn. A/S.

'Optical Particle Sizing Using the Phase of LDA Signals';  
Dantec Information No. 5, September 1987; Dantec Meas. Techn. A/S.

'Correction of constant Current Anemometry Reading in High-Frequency Temperature fluctuation measurements'; E. V. Shishov, P.S. Roganov, R.V. Klovikian and V.P. Zubolotsky;  
Dantec Information No.5, September 1987; Dantec Meas. Techn. A/S.

'Description of the DISA CTA System' Published by DISA Information Department  
[Dantec 55M System].

# **SUPERSONIC GAS-LIQUID CLEANING SYSTEM PROJECT**

## **MONTHLY PROGRESS REPORT**

March 10, 1995

This project report is submitted by Dr. Sunil K. David to Bethune Cookman College, and describes work performed during the sixth and the final month of the research project (Ref: TRDA Grant #411).

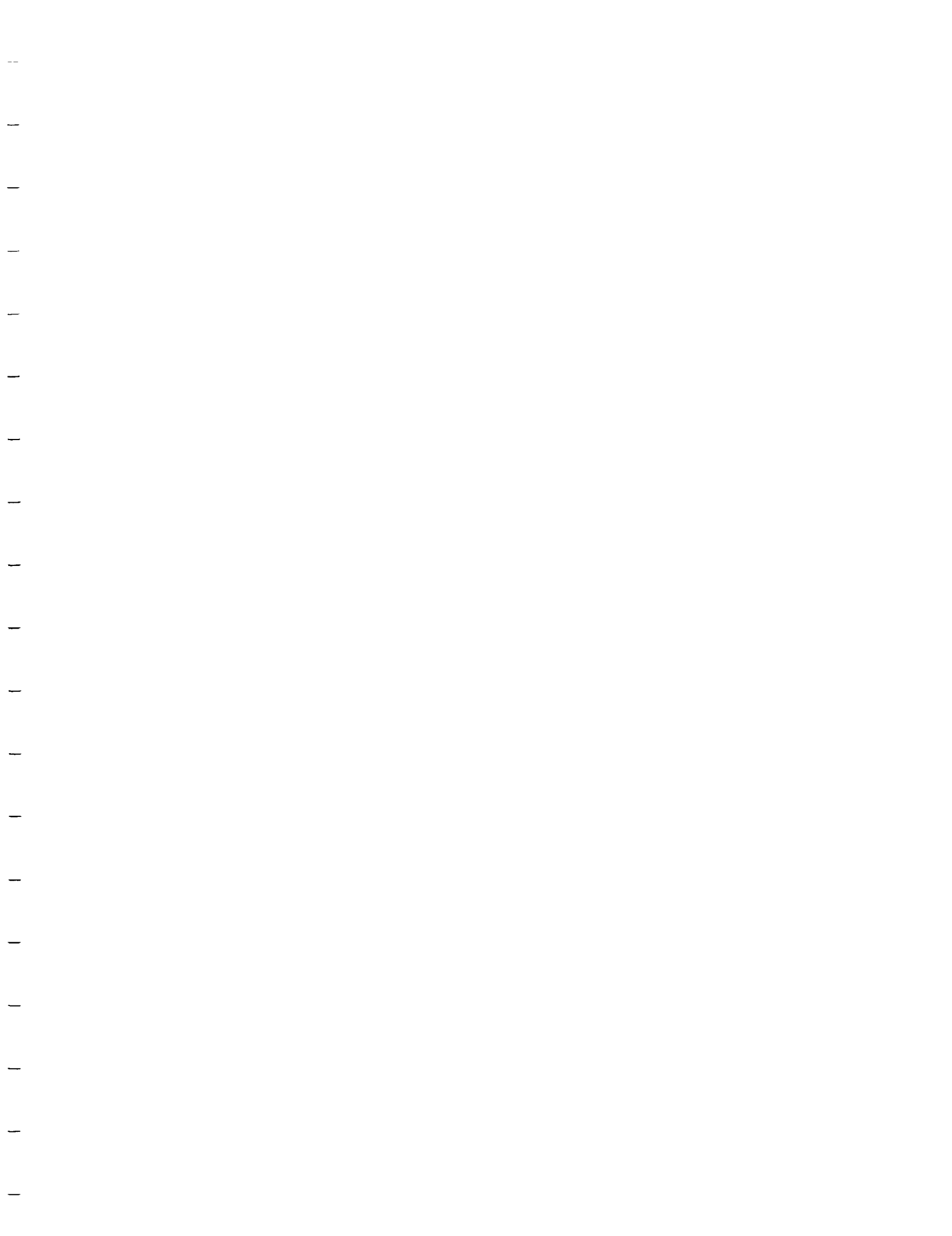
During the last week of February phase-III experiments were conducted at the NASA/Langley research station, to measure of the fluid velocity and the size distribution of the particles of air-water mixture in supersonic stream of the cleaning nozzle by a non intrusive method. As mentioned in last report, instrument facility of the Laser Transit Anemometry (LTA) was made available to us at the LaRC, Hampton, Virginia. The prototype nozzle and the control panel was transported to LaRC before hand. At LaRC all the necessary arrangements were made to setup the nozzle and the control panel, and LTA in a laboratory which has supply line of high pressure air and Life protection facilities. Tasks of optical and Mechanical alignments were also performed using standard techniques. Velocity of the particles in two-phase flow of air-water mixture was measured at the various axial distances from the exit plane for three upstream pressures (200, 300, and 400 psig) of the nozzle. The mass flow rate of water in the air-water stream was also measured at these working pressures. Though the ETA method is quite suitable for the absolute measurement of the velocity, it is not sensitive enough for determining particle sizes. However, experimental results indicated that particle size of the water droplets, on the average, is much less than 0.8 micron.

A detailed description of the above mentioned measurements are presented in the final consolidated report which includes tables, spread-sheets of the observations, ambient conditions, graphical plots, photographs etc. This report also contains details of other methods which were used to obtain experimental data on the performance of the prototype nozzle.

This report will not complete without acknowledging the personal help of Dr. William J. Humphreys in setting up the ETA system and collecting data. Thanks are also due to Dr. J. Meyers for allowing the use of facilities at Langley and for his expert advice.

A handwritten signature in black ink, reading "Sunil Kumar David", with a horizontal line underneath the name.





# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## MONTHLY PROGRESS REPORT

This progress report is submitted by Embry-Riddle Aeronautical University (ERAU) to Bethune Cookman College (BCC), and describes the work done during the fourth month under TRDA Grant #411 towards the development of a Supersonic Gas-Liquid Cleaning System.

Work continued on model development during this month. Last month's report discussed a simple code which was developed to check the validity of the model equations. In the simple code, the flow was assumed to experience constant acceleration as it moved through the nozzle. The code then was used to determine the variation of other properties across the nozzle; in particular, the area variation required for obtaining the specified constant acceleration was obtained.

The final code developed should, however, be capable of performing the reverse task. It should use a specified area distribution and determine the variations of velocity and other properties across the nozzle. This development was performed this month. To accomplish this, the model equations were cast in a modified form. Without this modification, solution of the equations would encounter numerical difficulties at the nozzle location where the gas speed became sonic. It should also be noted that the solution could not be commenced at the nozzle entry. The gas velocity was zero at this location and, therefore, the area approached infinity. Thus, the solution was obtained for some small initial length of the nozzle assuming constant acceleration. Then the specified area distribution was used to continue the integration to the nozzle exit.

The code described above is currently being used to perform parametric studies.

*L.L. Narayanaswami, Jan 12, 65*  
L.L. Narayanaswami

# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## MONTHLY PROGRESS REPORT

This progress report is submitted by Embry-Riddle Aeronautical University (ERAU) to Bethune Cookman College (BCC), and describes the work done during the fifth month under TRDA Grant #411 towards the development of a Supersonic Gas-Liquid Cleaning System.

Parametric studies were started this month using the model. The nozzle contour, see Figure 1, utilized in the cleaning system was used in these studies.

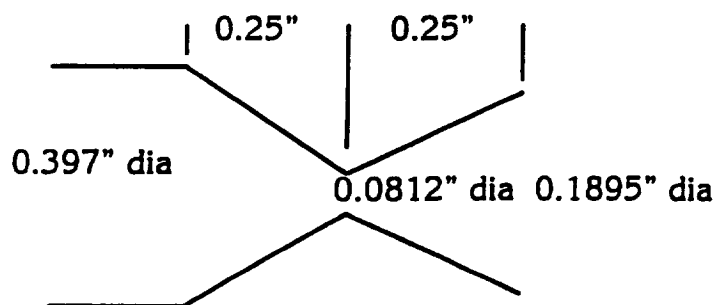


Figure 1: Nozzle Profile

As the integration was performed, numerical difficulties were experienced near the location where the Mach number was 1. The reason for this difficulty was that a variable  $Z$  (defined in the model) and its derivative  $dZ/dx^*$  approached zero near the location where the Mach number was 1. Owing to this problem, parametric studies were not completed this month.

Currently, integration is being carried out using very small step sizes near the  $M = 1$  location to overcome the problem.

Last week (week of Feb 6, 1995 to Feb 10, 1995), Mr. Matt La Vigne of TRDA required that a write-up of the model work be sent to him. Accordingly, a report was prepared and submitted to TRDA. A copy of the report is attached.

Also attached are summaries from some pertinent references located as a result of the literature search.

*L.L. Narayanaswami, Feb 13, '95*  
L.L. Narayanaswami

# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## NOZZLE MODEL DESCRIPTION

The model described in what follows describes a two-phase flow through a converging-diverging nozzle of a given geometry. The development closely follows that in Reference 1. As mentioned in the second monthly report, the model is based on the following assumptions: (1) the flow is steady and one-dimensional, (2) droplets are uniformly distributed in the mixture, (3) droplets are uniform in diameter, and have uniform properties, (4) drag between the gas and liquid phases can be described in terms of a mean velocity difference between them, (5) heat transfer between the phases can be related to the mean temperature difference between them and (6) there is no mass transfer between phases.

Subject to these assumptions, the following equations can be used to describe the two phase flow:

$$\text{Mass (Gas Phase):} \quad \rho u A = \dot{m} \quad (1)$$

$$\text{Mass (Particle Phase):} \quad \rho_p u_p A = \kappa \dot{m} \quad (2)$$

$$\text{Momentum (Gas Phase):} \quad \rho u \frac{du}{dx} + \frac{dp}{dx} = F_p \quad (3)$$

$$\text{Momentum (Particle Phase):} \quad \rho_p u_p \frac{du_p}{dx} = -F_p \quad (4)$$

$$\text{Energy (Gas Phase):} \quad \rho u C_p \frac{dT}{dx} - u \frac{dp}{dx} = (u_p - u) F_p + Q_p \quad (5)$$

$$\text{Energy (Particle Phase):} \quad \rho_p u_p C_s \frac{dT_p}{dx} = -Q_p \quad (6)$$

In the above equations,  $\rho$  and  $\rho_p$  represent the gas and particle densities,  $u$  and  $u_p$  denote the gas and particle velocities,  $T$  and  $T_p$  represent the gas and particle temperatures, and  $p$  is the pressure.  $\dot{m}$  and  $\kappa \dot{m}$  denote the gas and particle mass flow rates, and  $C_p$  and  $C_s$  are the gas and particle constant pressure specific heats. Utilizing assumptions (4) and (5), the drag force  $F_p$  and the heat transfer  $Q_p$  between the phases can be written as

<sup>1</sup>Hultberg, J.A. and Soo, S.L., "Two-Phase Flow through a Nozzle," *Astronautica Acta*, Vol. 11, No.3, 1965.

$$\text{Drag :} \quad F_p = f (u - u_p) \quad (7)$$

$$\text{Heat Transfer :} \quad Q_p = q (T - T_p) \quad (8)$$

where  $f$  and  $q$  are constants related to the gas and particle phase properties. Equations (3) and (4) may now be combined to get the overall momentum equation as follows:

$$\rho u \frac{du}{dx} + \rho_p u_p \frac{du_p}{dx} + \frac{dp}{dx} = 0 \quad (9)$$

Equations (5) and (6) could be used, in conjunction with Equations (3) and (4), to obtain the following overall energy equation:

$$(C_p T + \frac{u^2}{2}) + \kappa (C_s T_p + \frac{u_p^2}{2}) = \text{constant} \quad (10)$$

In the above equation, the constant can be determined by using the nozzle boundary conditions.

## NONDIMENSIONALIZING THE MODEL EQUATIONS

It is useful to nondimensionalize the equations governing the system. Accordingly, the various equations are nondimensionalized using reference variables  $p_0$ ,  $T_0$ ,  $\rho_0$ ,  $u_0$ ,  $L$  and  $(m/\rho_0 u_0)$ . In this list,  $p_0$  is the upstream tank pressure,  $T_0$  is the upstream tank temperature,  $\rho_0$  is the upstream tank density,  $u_0$  is  $\sqrt{2C_p T_0}$ , and  $L$  is the length of the nozzle. Thus, the equations are cast in terms of the following nondimensional variables:

$$\text{Normalized pressure } p^* = \frac{p}{p_0} \quad (11a)$$

$$\text{Normalized Gas Temperature } T^* = \frac{T}{T_0} \quad (11b)$$

$$\text{Normalized Particle Temperature } T_p^* = \frac{T_p}{T_0} \quad (11c)$$

$$\text{Normalized Gas Velocity } u^* = \frac{u}{u_0} \quad (11d)$$

$$\text{Normalized Particle Velocity } u_p^* = \frac{u_p}{u_0} \quad (11e)$$

$$\text{Normalized Area } A^* = \frac{A}{(\dot{m}/\rho_0 u_0)} \quad (11f)$$

$$\text{Normalized Length } x^* = \frac{x}{L} \quad (11g)$$

The normalized form of the equations are given below.

$$\text{Gas Mass : } p^* u^* A^* = T^* \quad (12)$$

$$\text{Particle Momentum : } u_p^* \frac{du_p^*}{dx^*} = C (u^* - u_p^*) \quad (13)$$

$$\text{Overall Momentum : } \frac{2 C_p}{R T^*} u^* \frac{du^*}{dx^*} + \frac{2 C_p}{R T^*} \kappa u^* \frac{du_p^*}{dx^*} + \frac{1}{p^*} \frac{dp^*}{dx^*} = 0 \quad (14)$$

$$\text{Particle Energy : } u_p^* \frac{dT_p^*}{dx^*} = D (T^* - T_p^*) \quad (15)$$

$$\text{Overall Energy : } T^* + u^{*2} + \kappa \frac{C_s}{C_p} T_p^* + \kappa u_p^{*2} = 1 + \kappa \frac{C_s}{C_p} \quad (16)$$

In the above set of equations, C and D are nondimensional equivalents of f and q, respectively. Further, it should be noted that the 'constant' on the right hand side of the dimensional form of the overall energy equation (Equation (10)) has been obtained by observing that, at the entrance to the nozzle from the tank ( $x^* = 0$ ),  $u^*$  and  $u_p^*$  are zero, and  $T^*$  and  $T_p^*$  are 1. This results in the 'constant' being evaluated to be  $(1 + \kappa C_s/C_p)$  as shown in Equation (16).

The five equations (12) through (16) describe the variation with  $x^*$  of six variables  $p^*$ ,  $T^*$ ,  $T_p^*$ ,  $u^*$ ,  $u_p^*$  and  $A^*$ . If the variation of one of these variables with  $x^*$  is known, then the five equations can be used to obtain the variation of the other five with respect to  $x^*$ . In particular, the flow properties at the exit plane of the nozzle can be obtained.

## INITIAL CALCULATIONS USING MODEL EQUATIONS

In order to verify the accuracy of the model equations, preliminary calculations were performed by assuming the gas velocity to be known through the nozzle. A simple variation, namely that  $u^*$  varies linearly with  $x^*$ , was assumed ( $u^* = \alpha x^*$ ). Then, Equations (12) through (16) were used to determine the variation of the other variables with  $x^*$ . The appropriate boundary conditions at the nozzle entrance ( $x^* = 0$ ) were  $p^* = 1$ , and, as mentioned in connection with Equation (16) above,  $u_p^* = 0$ ,  $T^* = 1$  and  $T_p^* = 1$ .

In performing these calculations, the following values were assumed for the several constants appearing in the model:  $D = 10.$ ,  $C = 100.$ ,  $C_p = 1004.5$  J/kg-K,  $C_s = 494$  J/kg-K,  $R = 287$  J/kg-K and  $\kappa = 0.3$ . In addition, the constant relating  $u^*$  to  $x^*$  (the quantity  $\alpha$  in  $u^* = \alpha x^*$ ) was taken to be 0.9. The results of the calculations are shown in Figure 1.

## SOLUTION FOR ARBITRARY AREA RATIOS

While the solution described in the previous section is useful as a reference operating characteristic, the variation of the gas velocity through the nozzle is not readily available in practical situations. More usually,  $A^*$  would be known as a function of  $x^*$ . Thus, it is necessary to develop a solution methodology that would utilize the model equations (Equations (12) through (16)) to determine the variation of  $u^*$ ,  $u_p^*$ ,  $T^*$ ,  $T_p^*$  and  $p^*$  with  $x^*$  for any arbitrary nozzle profile ( $A^*(x^*)$ ). The methodology is described in this section.

A close inspection of the equation set shows that singularities are present in the expressions for  $dp^*/dx^*$ ,  $dT^*/dx^*$  and  $du^*/dx^*$ . The singularities occur at the location in the nozzle where the Mach number (based on the speed of sound in gas only) becomes 1. Consequently, the equations have to be recast in a form suitable for solution. This requires the introduction of an auxiliary variable Z defined to be  $1/2(M^2 - 1)^2$ , where M is the Mach number based on the speed of sound in gas. The resulting equation set is presented below:

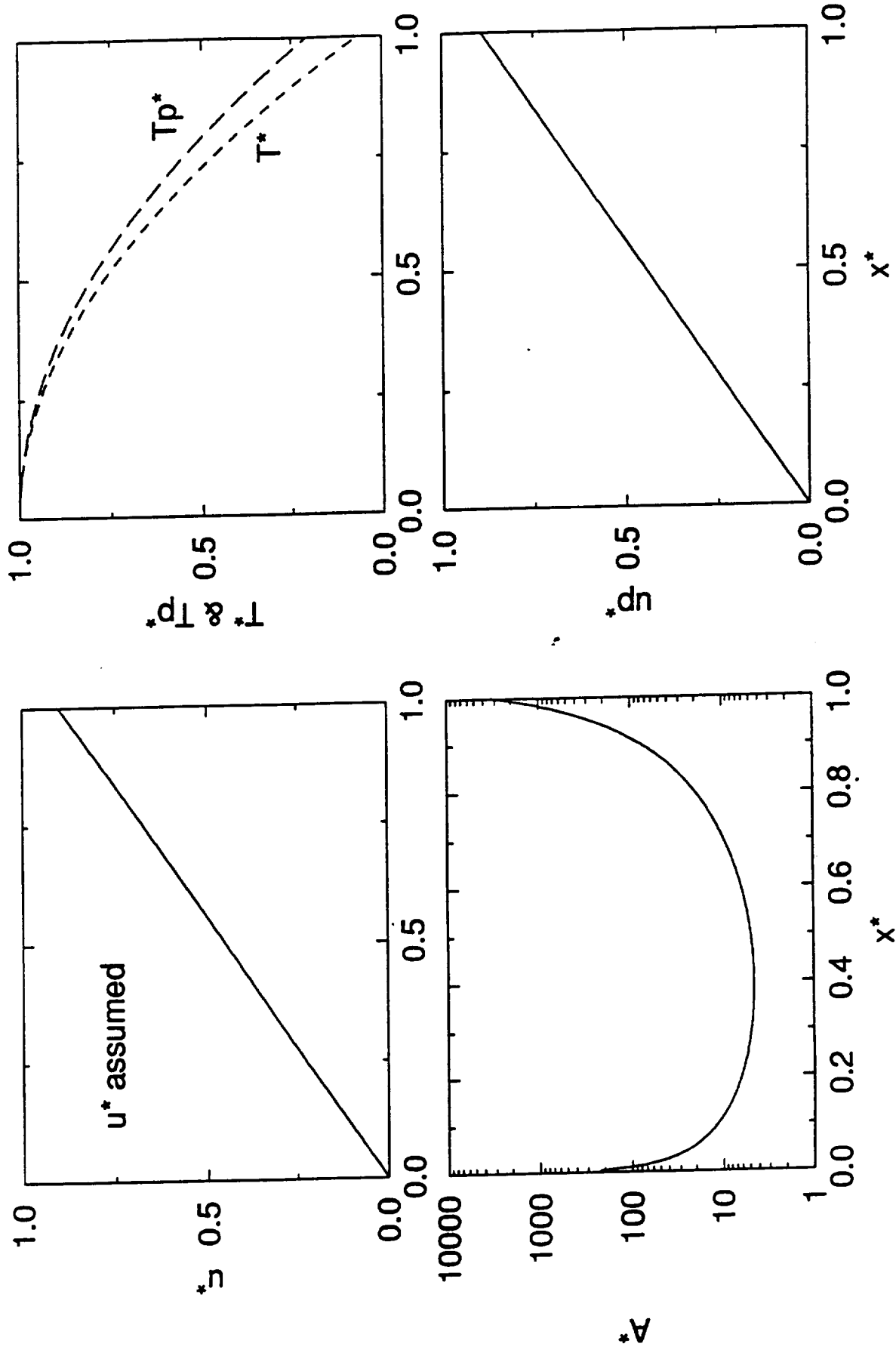


Figure 1: Solution for Linear Velocity Variation



$$u_p^* \frac{du_p^*}{dx^*} = C (u^* - u_p^*) \quad (13)$$

$$u_p^* \frac{dT_p^*}{dx^*} = D (T^* - T_p^*) \quad (15)$$

$$\begin{aligned} \frac{dZ}{dx^*} = 2M^2 \left( \frac{1}{T^*} + \frac{u^{*2}}{T^{*2}} \right) & \left[ \frac{T^*}{A^*} \frac{dA^*}{dx^*} - \left( \frac{2C_p \kappa u^*}{R} - 2\kappa u_p^* \right) \frac{du_p^*}{dx^*} \right. \\ & \left. + \frac{\kappa C_s}{C_p} \frac{dT_p^*}{dx^*} \right] + (M^2 - 1) \frac{2C_p u^{*2}}{\gamma R T^{*2}} \left[ \frac{\kappa C_s}{C_p} \frac{dT_p^*}{dx^*} + 2\kappa u_p^* \frac{du_p^*}{dx^*} \right] \end{aligned} \quad (17)$$

$$T^* + u^{*2} + \kappa \frac{C_s}{C_p} T_p^* + \kappa u_p^{*2} = 1 + \kappa \frac{C_s}{C_p} \quad (16)$$

$$Z = \frac{1}{2} (M^2 - 1)^2 \quad \text{OR} \quad M^2 = 1 \mp \sqrt{2Z} \quad (18 \text{ a\&b})$$

$$u^{*2} = T^* M^2 \frac{\gamma R}{2C_p} \quad (19)$$

The above set of six equations ((13), (15), (16), (17), (18 a) and (19)) describes the variation of 7 variables ( $u_p^*$ ,  $T_p^*$ ,  $Z$ ,  $A^*$ ,  $T^*$ ,  $u^*$  and  $M$ ) with  $x^*$ , the distance along the nozzle. If the nozzle profile information ( $A^*(x^*)$ ) is known, the above set can be solved to obtain the variation of the other six variables with  $x^*$  by making use of the boundary conditions at  $x^* = 0$ :

$$T^* = T_p^* = 1; u^* = M = u_p^* = 0; Z = 0.5 \quad (20)$$

It should be noted that in performing the integration, the negative sign in Equation (18 b) applies to subsonic flow, and the positive sign to supersonic flow. Thus, as integration is carried out from  $x^* = 0$ , the negative sign is used until the location where  $M$  reaches

unity. The applicable sign in Equation (18 b) is then positive as solution is extended to the supersonic regime.

It should also be noted that the integration cannot be started at  $x^*$  of zero, since  $A^*$  goes to infinity there. Consequently, an alternate solution has to be assumed over some initial distance in the nozzle. In this work, the linear gas velocity variation ( $u^* = \alpha x^*$ ), discussed elsewhere, is assumed in the initial region (say, from  $x^* = 0$  to  $x^* = 0.03$ ). The solution is then continued using the specified nozzle profile.

To get the correct solution, the value of  $\alpha$  cannot be arbitrarily chosen since each value of  $\alpha$  corresponds to a particular nozzle profile (recall the particular  $A^*$  variation obtained with  $\alpha = 0.9$ , see Figure 1). Thus, the chosen value of  $\alpha$  has to be checked for correctness. If found to be incompatible with the specified nozzle profile, it has to be suitably corrected. This checking and correcting is performed at the nozzle throat, as described below.

It can be shown that the gas velocity  $u^*$  at the throat is given by the following analytical expression:

$$u_t^{*2} = a_m^{*2} \left[ 1 + \kappa \frac{du_p^*}{du^*} \right]^{-1} \quad (21)$$

where  $u_t^*$  and  $a_m^*$  are, respectively, the gas speed at the throat and the speed of sound in the mixture. By comparing the values of  $u_t^*$  obtained from the numerical solution with that from Equation (21), the correctness of the choice of  $\alpha$  is determined. If the velocities do not agree, then an  $\alpha_{new}$  is obtained as

$$\alpha_{new} = \alpha_{old} + \delta\alpha; \quad \delta\alpha = \eta \frac{u_t^{*exact} - u_t^{*num}}{x_t^*} \quad (22)$$

where  $\eta$  is a constant less than one, and  $x_t^*$  denotes the throat location.

It should be pointed out that numerical integration is difficult near the region where the Mach number  $M$  based on the speed of sound in the gas becomes unity. Around this condition, both  $Z$  and  $dZ/dx^*$  approach zero, and the solution should be carefully advanced from one  $x^*$  to the next.

To check the solution technique for arbitrary area ratios, the nozzle profile computed with  $u^* = \alpha x^*$  was used. This profile was used as input to see if the technique recovered the linear velocity variation, and the other variations exactly as depicted in Figure 1. The solution was obtained by taking  $\alpha$  to be 0.9 (thus, no iteration was necessary here using Equations (21) and (22) to obtain the correct  $\alpha$ ). Figure 2 presents the results. It can be seen that the method has successfully computed the values of the different variables.

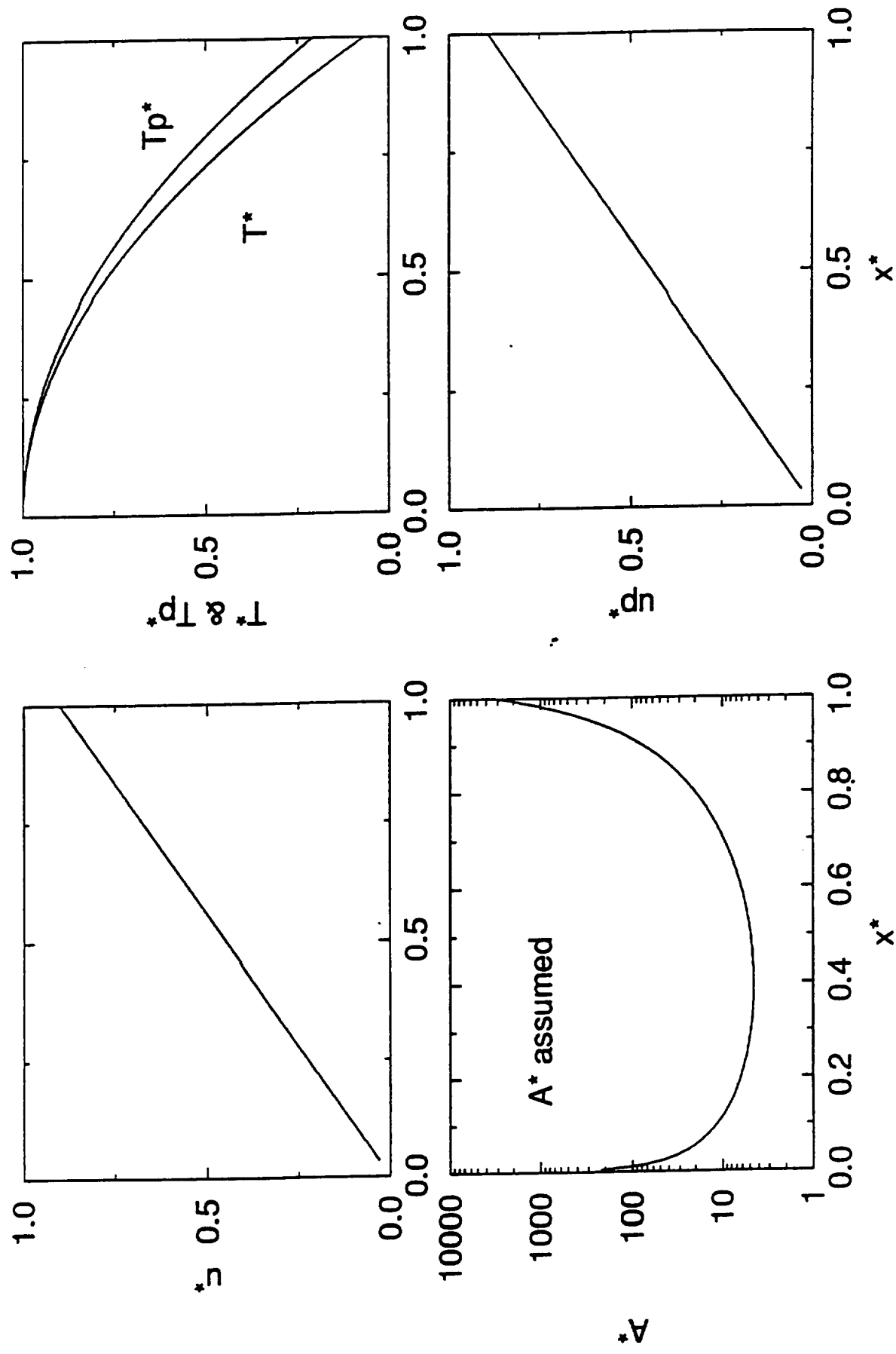


Figure 2: Solution with Specified Area Variation

## SUMMARY OF REFERENCES

'A NUMERICAL SIMULATION OF INJECTION OF DROPLETS IN A COMPRESSIBLE FLOW',  
Daniel, E., Larini, M., Loraud, J-C., Porterie, B.

A numerical simulation of the injection of water droplets into a 2D, unsteady, inviscid compressible nozzle flow is computed. A two fluid (Eulerian-Eulerian) system was obtained by a weak conservative balance analysis of the gas phase and the dispersed phase. Each phase was considered a continuum. Drag, heat and mass transfers between the two phases are taken into account.

Previous works by Chang (Ref 1. and 2.) considered two phase (gas-particle) flow in two and three dimensions. Golafshani et al (Ref 3.) had previously considered treating the dispersed phase as a discreet one and a Eulerian-Lagrangian model was solved through the use of a finite-volume method. The drawback to using such a method is the required interpolations between the Lagrangian grid (droplets) and the Eulerian grid (gas). The Eulerian-Eulerian method requires

The governing equations were written in the weak conservative form. The energy equation for the dispersed phase reduces to the saturation temperature which indicates that the heat flux from the gas to the droplet is completely used in vaporization. This means that break-up or coalescence of droplets is neglected. An energy balance around one droplet is used to determine the mass transfer from the droplet. Yuen and Chen (Ref 4.) showed there is a diminution of heat transfer due to mass exchange. A correction to the classical correlation of the Nusselt number was used to obtain the expression of the heat transfer. This corrected Nusselt number correlation is also applied to the drag transfer (Ref 5.) All the thermophysics variables are assumed constant except the latent heat of vaporization, the saturation temperature and the droplet enthalpy, all of which depend on the gas pressure.

The MacCormack finite difference scheme was used to solve the partial differential equations. The boundary conditions are detailed for both phases.

The results were not compared to experimental data because no experimental data was available for the injection of droplets into compressible nozzle flow.

The results for steady flow were qualitatively compared to previous two-phase nozzle flow works. The two phase nozzle flow compared favorably with that of Chang. The droplet size was found to be the most important factor in affecting the droplet free zone in the nozzle. The void fraction was found to have no effect on this zone.

Contours of the normalized number of droplets per unit volume are plotted for several times after droplet injection until the steady state is reached. In this paper the object of the droplet injection was to cool the gas and gas temperature contours are plotted for a sample nozzle at several times until the steady state was reached.

### References;

1. I-Shin Chang. 'One and two-phase flows', AIAA Journal, Vol 18, 1980
2. I-Shin Chang. 'Three dimensional two-phase supersonic nozzle flows', AIAA Journal, Vol 21, 1983
3. Mehdi Golafshani, Hai-Tien Loh, 'Computation of two-phase viscous flow in solid rocket motors using a flux split Eulerian-Lagrangian Technique', aiaa/asme/asee 25th Joint Propulsion Conference, Monterey California
4. M. C. Yuen, L. W. Chen, 'Heat transfer measurements of evaporating liquid droplets', International Journal of Heat and Mass Transfer, Vol 27, 1977
5. J. N. Chung, S. I. Olafsson, 'Two-phase droplet flow convective and radiative heat transfer', International Journal of Heat and Mass Transfer, Vol 27, 1983

Modern propulsion systems usually have small throat radii, steep wall gradients at the entrance or submerged configuration nozzles in the interest of minimizing length and weight. A review of gas-particle nozzle flowfield investigations before 1962 was presented in Ref 2. More recent work includes the numerical iteration relaxation technique (Ref. 3) and an uncoupled flow model (Ref. 4). These studies help to explain some of the physical processes of gas-particle transonic flows but all used the assumption of the fixed gas-phase streamline coordinates. This assumption is not true for steep geometries or small throat curvatures where the presence of particles will change the flow behavior. This paper analyses the time dependant, gas only and two-phase, inviscid, compressible flow in nozzles of arbitrary geometry.

The equations of state are written in the weak conservative form for the unsteady, inviscid, transonic gas only and gas-particle flow inside nozzles with small throat radii of curvature, steep wall gradients and submerged configurations. The friction, heat, drag, energy and momentum transfers are taken into account. Henderson's correlation equation (Ref. 6) and Stokes law of drag coefficient for spheres in creeping motion are used in the momentum transfer. The particle Nusselt number is used in the heat-transfer (Ref 5.).

Successive over-relaxation was utilized to generate the boundary fitted coordinates, BFC, (Ref. 7) through the use of the TOMCAT computer program. The FATCAT program (Ref 7.) was utilized to determine the scale factors needed to transform from the physical grid to the computational plane. The MacCormack finite difference scheme (Ref 8.) was applied to solve the transformed differential equations.

For one phase flow, the initial condition was based on a one-dimensional, isentropic flow analysis. An interpolation was used to obtain the gas only flow results and these were used as the initial estimate for the gas-phase in the two-phase flow. The two-phase boundary conditions are discussed. The fourth order damping terms to the second order MacCormack method were retained to prevent nonlinear instability (Ref. 9).

The solution method was applied to JPL nozzle, the Titan III solid rocket motor and the submerged nozzle configuration in the inertial upper stage solid rocket motor. This led to the following applicable conclusions: the MacCormack finite-difference method results in stable integration for both one and two-phase nozzle flow equations; BFC system improves the program capability to allow solution of flows inside complex geometry nozzles; small size particles slow down the gas phase expansion more than large size particles for a constant particle mass fraction; a high particle loading ratio can cause the gas phase to be subsonic at the throat; a constant fractional lag is not justified for a two-phase transonic flow and the requires the momentum and energy exchange to be taken into account.

#### References

1. Brown, E. F., Hamilton, G. L., 'A survey of Methods for exhaust-nozzle flow analysis', AIAA Paper, 1975
2. Hoglund, R. F., 'Recent advances in gas-particle nozzle flows', ARS Journal, May 1962
3. Regan, J. F., Thompson, H. D., Hoglund, R. F., 'Two dimensional analysis of transonic gas-particle flows in axisymmetric nozzles', Journal of Spacecraft and Rockets, Vol. 8, April 1971
4. Jacques, L. J., Sequin, J. A. M., 'Two dimensional transonic two-phase flow in axisymmetric nozzles', AIAA Paper, October 1974
5. Carlson, D. J., Hoglund, R. F., 'Particle drag and heat transfer in rocket nozzles', AIAA Journal, Vol 2, Nov 1964
6. Henderson, C. B., 'Drag coefficients of spheres in continuum and rarefied flows', AIAA

Journal, Vol 14, June 1976

7. Thompson, J. F., Thames, F. C., Martin, C. W., 'Boundary fitted curvilinear coordinates systems for solution of partial differential equations on fields containing any number of arbitrary two-dimensional Bodies', NASA CR 2729, July 1977
8. MacCormack, R. W., 'The effect of viscosity in hypervelocity impact cratering', AIAA Paper, May 1969
9. Kutler, P., Sakell, L., Aiello, G., 'On the shock-on-shock interaction problem', AIAA Paper, June 1974

'TWO PHASE FLOW THROUGH A NOZZLE', Hultberg, J. A., Soo, S. L., *Astronautica ACTA*, Vol II, No 3, 1965

Gas-particle two phase, one dimensional, supersonic flow in a nozzle was analyzed for spherical particles. Drag force, momentum and heat transfer between the phases was considered. The throat condition was obtained by setting the change in area with respect to distance measured along the longitudinal axis equal to zero. This led to the throat condition that the gas velocity is subsonic at the throat even when wall friction is neglected. The Runge-Kutta-Gill method (Ref. 1) was used. The boundary conditions were determined. The theoretical results were compared to experimental data and were found to be significantly different. The one dimensional flow assumption was shown to be inadequate when compared to the experimental data.

#### References

1. Gill, S., 'A process for the step-by-step integration of differential equations in an Automatic Digital Computing Machine', *Proc. Cambridge Phil. Soc.*, 1951

'THREE DIMENSIONAL, TWO-PHASE SUPERSONIC NOZZLE FLOWS', I-Shin Chang, *AIAA Journal*, Vol 21, No 5, May 1983

The governing equations for a gas-particle, three dimensional, steady flow were written in the weak conservative form. The exchange of friction, heat, energy and momentum between the two phases was taken into account. Once again Stokes drag coefficient and Henderson's correlations were used (Ref. 1 and 2).

The equations were transformed into a cylindrical coordinate system (Ref. 3) before solution through the use of the MacCormack method of finite differences (Ref. 4.) A stability analysis calculation procedure (Ref. 3) was utilized. A tangent condition was applied for both the gas and the particle phase at the boundary surface. The Abbett scheme (Ref. 5) for determining gas phase boundary flow variables was modified to account for entropy changes at the boundary. Further boundary flow conditions are discussed.

#### References

1. Henderson, C. B., 'Drag coefficients of spheres in continuum and rarefied flows', *AIAA Journal*, Vol 14, June 1976
2. Carlson, D. J., Hoglund, R. F., 'Particle drag and heat transfer in rocket nozzles', *AIAA Journal*, Vol 2, November 1964
3. Chang, I-S., 'Three dimensional supersonic internal flows', *AIAA Paper*, July 1976
4. MacCormack, R. W., 'The effect of viscosity in hypervelocity impact cratering', *AIAA Paper*, May 1969
5. Abbett, M. J., 'Boundary condition calculation procedures for inviscid supersonic flow fields', *Proceedings of the AIAA Computational Fluid Dynamics Conference*, Palm Springs, California, July 1973

**'SUPERSONIC GAS-LIQUID CLEANING SYSTEM', Caimi, Raoul E. B., Thaxton, Eric A.**

Introduces the supersonic gas-liquid cleaning concept to replace the current hot, solvent flush method used to clean liquid oxygen systems at Kennedy Space Center. The performance which must exceeded in order to replace the current system are detailed. A handheld prototype system was build and successfully tested.

One dimensional, irrotational, frictionless gas flow equations were used with a dispersed phase of droplets. Homogeneous, adiabatic, uniform velocity flow was assumed. The equation of state and the expansion law assuming an isentropic process was derived. An isentropic flow table was constructed and this was used to determine the Mach number versus area ratio.

A handheld prototype system using nitrogen and distilled water built and successfully tested. Additional applications were discussed.

**'A COMPARISON BETWEEN CENTERED AND UPWIND SCHEMES FOR TWO-PHASE COMPRESSIBLE FLOWS', Daniel, E., Saurel, R., Larini, M., Loraud, J. C., AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, June 1993, Monterey, California**

Two different methods were developed to analyze two dimensional, two-phase flow through an Eulerian approach. The different assumptions used which lead to conservative or nonconservative systems and to hyperbolic or degenerative hyperbolic systems are discussed.. One flow system was solved by a central scheme and a second system was solved by an upwind scheme. A Riemann solver for a dilute dispersed was included in the upwind scheme. The results of the two different schemes were found to be comparable. The differences in the boundary conditions were thought to have led to the differences between the results. The upwind scheme was shown to accurately solve two-phase PDE in complex geometries. The central scheme could solve any two-phase flow that can be described

**References**

1. Chang, I-S., 'One and two-phase nozzle flows', AIAA Journal, Vol 18, 1980
2. Chang, I-S., 'Three dimensional two-phase supersonic nozzle flows', AIAA Journal, Vol 21, 1983
3. Daniel, E., Larini, M., Loraud, J. C., Porterie, B., 'A numerical simulation of injection of droplets in a compressible flow', 27th Thermophysics Conference AIAA Paper, Nashville, TN, 1992

**'EFFECTS OF COMPRESSIBILITY ON ATOMIZATION OF LIQUID JETS', Zhou, Z. W., Lin, S. P., AIAA 30th Aerospace Sciences Meeting & Exhibit, Reno, Nevada, 1992**

The effects of compressibility of fluids on the atomization of a liquid jet emanating from a nozzle into the ambient gas was investigate through the use of a linear stability analysis. Increased compressibility of the liquid jet was shown to result in smaller droplets generated at a lower rate. It was also shown that small changes in compressibility result in a qualitative change of the mechanism of atomization.

**'NUMERICAL METHODOLOGIES FOR THE COMPRESSIBLE NAVIER-STOKES EQUATIONS FOR TWO-PHASE FLOWS', Grasso, F., Magi, V., Modern Research Topics in Aerospace Propulsion, Pringer-Verlag**

In this large paper (33 pages) the physics of sprays and numerical methods for the solution of the compressible, two-phase Navier-Stokes equations are reviewed and a new numerical method is derived. The results from this method are compared to experimental data for sprays in selected conditions.





# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## PROJECT STATUS REPORT NO. 4

JANUARY 12, 1995

This project status report is submitted by Precision Fabricating and Cleaning Co., Inc. (PFC) to Bethune-Cookman College (B-CC), and describes work performed between December 8, 1994 and January 10, 1995 in support of this research project (Ref. TRDA Grant # 411).

Dr. David and Tom Jezowski have begun testing of the nozzle system. This testing is taking place at Precision Fabricating and Cleaning in their Mobile Clean Room Facility.

On December 14, 1994 we received the Breathing Air tube bank trailer (GT-13) here at PFC. The NASA prototype lab finished fabrication of the second nozzle on December 16 and we picked it up. The hot-wire anemometer became available to us on December 19 but it did not come with any type of probe. Dr. David chose a hot-film type of probe and B-CC procured it from the manufacturer. The probe arrived at B-CC around the end of December.

All the equipment setup and connections were completed by January 3, 1995 and Dr. David brought the hot-film probe to PFC on January 4, 1995. We began testing and were able to get consistent, repeatable velocity measurements. So far testing has been performed using gas only, at pressures ranging from 200 to 500 psig. Additional testing was performed on January 6th and 10th. Testing will continue on January 12th and 13th.

Kristen Riley and Kathleen Harer came out on January 6th to observe our equipment setup. Unfortunately we had temporary equipment problems and could not demonstrate full scale testing while they were here, but we did fix the problem and resume testing the following morning.

On January 10th we finished fabrication of the water injection assembly and connected it into the existing nozzle system. Dr. David and Tom Jezowski began initial testing using the gas-liquid mixture. Further testing will continue with this setup.

The next phase of testing will incorporate the use of either a supersonic pitot tube or a Laser Doppler Velocimeter or maybe both. This will be determined by availability of the equipment and whether or not it is necessary.

The data gathered so far, and in the future, will be used by Dr.'s David and Narayanaswami to verify and "fine tune" the computer model developed by Dr. Narayanaswami. Once the model is fully developed it will be used to optimize the nozzle design prior to actual fabrication of another nozzle.

Maria Littlefield, Kathleen Harer, Kristen Riley, Eric Thaxton, and possibly others are scheduled to come out to PFC on January 12 to observe the equipment setup and testing being performed by Dr. David and Tom Jezowski.

*Tom Jezowski 1/11/95*

# SUPERSONIC GAS-LIQUID CLEANING SYSTEM

## PROJECT STATUS REPORT NO. 5

FEBRUARY 13, 1995

RECEIVED

FEB 20 1995

Vice President for Academic  
Affairs/Dean of the Faculty

This project status report is submitted by Precision Fabricating and Cleaning Co., Inc. (PFC) to Bethune-Cookman College (B-CC), and describes work performed between January 11, 1995 and February 10, 1995 in support of this research project (Ref. TRDA Grant # 411).

Initial testing of the gas-liquid mixture was begun on January 11, 1995. Observation of the flow characteristics was the first stage of this testing. During these observations the hot-film anemometer probe was inadvertently destroyed. The probe was not repairable. The data gathered with the probe using gas only was quite consistent and as expected. Also, now that Dr. David has received the calibration curve from Dantec this data can be validated.

Efforts were made to locate a supersonic pitot tube but these efforts were unsuccessful. Investigation into procuring this type of probe proved to be cost prohibitive. Dr. David and Tom Jezowski fabricated a pitot tube at P.F.C.'s facility using small copper tubing and a hypodermic needle. This pitot tube was coupled to a pressure transducer and strip chart recorder supplied by NASA.

This pitot tube configuration was used to gather data from the gas-liquid stream. Numerous pressure readings were taken over several days and Dr. David is in the process of analyzing this data. The nozzle system, pitot tube, and data gathering equipment remain in place in case further testing is required to verify any of the data already gathered.

Several black and white photographs of the shock waves exiting the nozzle were taken. The photographs turned out well. Even with water introduced into the system the shock waves were still visible.

The next phase of testing will involve the use of a LDV located at NASA Langley. Dr. David, Maria Littlefield, and Eric Thaxton have already made one trip up to Langley to discuss this type of testing with the personnel familiar with this equipment. I believe arrangements are currently being made to transport the nozzle system up to Langley.

The data gathered from the experimentation performed at P.F.C. will be used to fine tune the computer model developed by Dr. Narayanaswami. This model will then be used to determine the optimal geometric design of the nozzle. Once this optimal design is determined, this nozzle should be fabricated and tested.

*Thomas S. Jezowski*

**ATTACHMENT “B”**

**Supersonic Gas-Liquid Cleaning System Research Project  
Final Project Budget Summary**

**Research Project Entitled:**  
**SUPERSONIC GAS-LIQUID CLEANING SYSTEM**

**FINAL ACTUAL PROJECT BUDGET**

Project Period:

August 01, 1994 - January 31, 1995

\* Extended to September 11, 1995

	NASA SHARE	TRDA SHARE	TOTAL COST
<b>A. Direct Labor</b>	<b>\$5,000</b>	<b>\$12,453</b>	<b>\$17,453</b>
TRDA Program Director (15% time)			
TRDA Contract Manager (15% time)			
TRDA Secretarial Support (5% time)			
<b>B. Travel (between TRDA, B-CC, E-RAU, PFC)</b>	<b>\$0</b>	<b>\$56</b>	<b>\$56</b>
<b>C. Other Direct Costs</b>	<b>\$0</b>	<b>\$2,898</b>	<b>\$2,898</b>
<b>D. Indirect Costs (TRDA @ 5%)</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>
<b>E. Subcontracts</b>			
<b>1 Bethune-Cookman College</b>			
a. Contract Mgmt.	\$15,866		\$15,866
b. Faculty Stipends (3)	\$12,000		\$12,000
c. Co-Op Students (3)	\$1,480		\$1,480
d. Travel	\$2,123		\$2,123
e. Subcontracts	\$25,000		\$25,000
1. Embry-Riddle Aero. Univ.			
(assistance in theoretical			
analysis of system)			
2. Precision Fabricating &	\$20,000		\$20,000
Cleaning Co., Inc.			
(assistance in commercial			
configurations/testing)			
f. Indirect Costs (B-CC)	\$1,614		\$1,614
<b>F. Equipment</b>	<b>\$815</b>		<b>\$815</b>
<b>TOTAL COSTS:</b>	<b>\$83,898</b>	<b>\$15,407</b>	<b>\$99,306</b>

**\$16,102**    *unspent NASA funds  
returned (de-obligated) to NASA*

**Research Project Entitled:**

**SUPERSONIC GAS-LIQUID CLEANING SYSTEM**

**PROPOSED BUDGET**

Project Period:

August 01, 1994 - January 31, 1995

\* Extended to September 11, 1995

		NASA SHARE	TRDA SHARE	TOTAL COST
<b>A. Direct Labor</b>				
TRDA Program Director (15% time)		\$2,129	\$3,530	\$5,659
TRDA Contract Manager (15% time)		\$2,871	\$574	\$3,445
TRDA Secretarial Support (5% time)		\$0	\$595	\$595
<b>B. Travel (between TRDA, B-CC, E-RAU, PFC)</b>		\$0	\$500	\$500
<b>C. Consultants (as needed - technology transfer,     engineering, project consultants)</b>		\$0	\$450	\$450
<b>D. Indirect Costs (TRDA @ 5%)</b>		\$0	\$5,000	\$5,000
<b>E. Subcontracts</b>				
1 Bethune-Cookman College		\$95,000	\$0	\$95,000
a. Contract Mgmt.	\$12,500			
b. Faculty Stipends (3)	\$18,000			
c. Co-Op Students (3)	\$15,000			
d. Travel	\$2,000			
e. Subcontracts				
1. Embry-Riddle Aero. Univ.	\$25,000			
(assistance in theoretical analysis of system)				
2. Precision Fabricating & Cleaning Co., Inc.	\$20,000			
(assistance in commercial configurations/testing)				
f. Indirect Costs (B-CC)	\$2,500			
<b>TOTAL COSTS:</b>		<b>\$100,000</b>	<b>\$10,649</b>	<b>\$110,649</b>

**ATTACHMENT “C”**

**Supersonic Gas-Liquid Cleaning System Research Project  
Final Project Reports**

# **SUPERSONIC GAS-LIQUID CLEANING SYSTEM**

( TRDA Research Project, Grant #411 )

FINAL TECHNICAL REPORT  
( *Consolidated* )

March 22, 1995

Submitted by

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# **SUPER-SONIC NOZZLE PROJECT**

## **1. BACKGROUND**

A proof-of-concept prototype of the supersonic gas-liquid cleaning system has been developed<sup>1</sup> and demonstrated at NASA, Kennedy Space Center. Presently, this system is being implemented as a cleanliness verification tool in replacement of CFC-113 rinsing. The system uses the high momentum of a supersonic air-liquid jet to remove contaminants from components while simultaneously emulsifying those contaminant into liquid jet (typically water). The liquid can be collected and sampled for contaminants to verify cleanliness. Extremely low volumetric flow rates of liquid are required with this system. NASA looked for a company that is interested in developing this system for commercial cleaning and cleanliness verification operations. The schematic diagram of the system is given in Fig.1 and the mechanical dimensions of the prototype nozzle are shown in Fig.2.

Under a research project of Technology Research and Development Authority (TRDA), NASA/KSC, Precision Fabrication & Cleaning company, Bethune-Cookman College (B-CC), and Embry-Riddle Aeronautical University (E-RAU) has jointly conducted study consisting of analysis and testing of the prototype cleaning system. Various tasks performed by these members are as follows:

1. Modeling of fluid mechanics and nozzle flows,
2. Parametric studies using the model,
3. Optimization of design,
4. Application to different matrixes,
5. Commercial nozzle configurations.

Embry-Riddle Aeronautical University (ERAU) did the modeling of the fluid mechanics and nozzle flows. Under the assumptions of steady state one dimensional flow, uniform droplet properties, drag between liquid and gas phases, heat and mass transfers between the phases, equations for mass, momentum and energy can be written for the two phases. In the extreme case of the liquid and gas phases having the same velocity and temperature (zero lag), the equations used by Caimi and Thaxton<sup>2</sup> are recovered. If the lag is small, but not zero, perturbation techniques provide the needed solution to the problem. In general, however, the lag will not be zero or small, and numerical methods are required to solve the equations in this work, this general condition of finite (not zero or small) lag is assumed.

Bethune-Cookman College (B-CC) designed and conducted experiments in collaboration with PF&C and NASA/Langley Research Center (NASA/LaRC) through NASA/KSC to obtain the required data to confirm the theoretical model(s) and the validity of the assumptions. In order to do this, measurement of the nozzle flow parameters were done at different values of the independent parameters.

This technical report presents details of these experimental investigations.

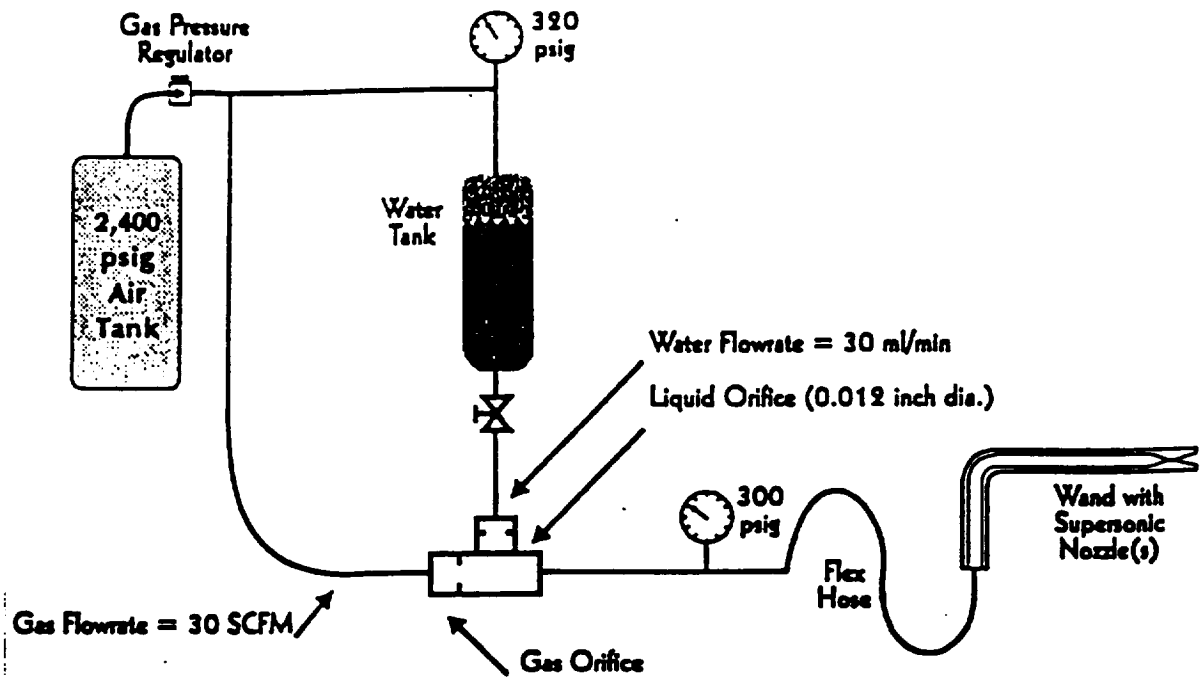


Fig.1 Schematic diagram of the Supersonic Gas-Liquid Cleaning System

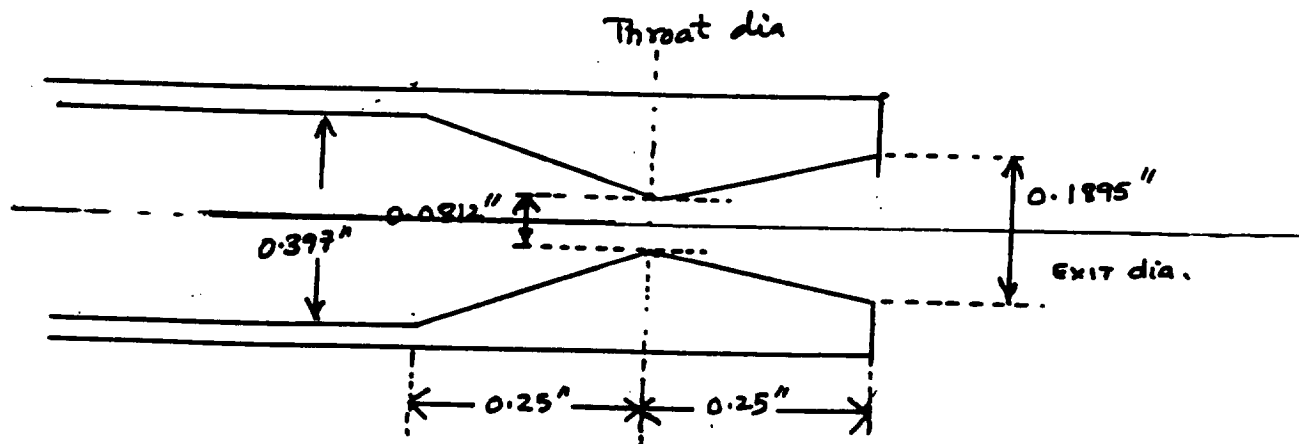


Fig.2 Mechanical dimensions of the mouth of the proto-type nozzle

## 2. The Supersonic Nozzle

The nozzle is the main part of the supersonic gas-liquid cleaning system(SGLCS). The geometrical dimensions of the prototype nozzle under investigation are given in Fig.2. This converging-diverging type nozzle is made of steel and has throat diameter of 0.0812". Normally the SGLCS is operated and with upstream pressure (tank pressure) of nozzle around 300 psig. It can be shown that velocity of a compressible fluids like air and air-water mixture (with very small amount of water) will be in supersonic range at the exit plane of the nozzle.

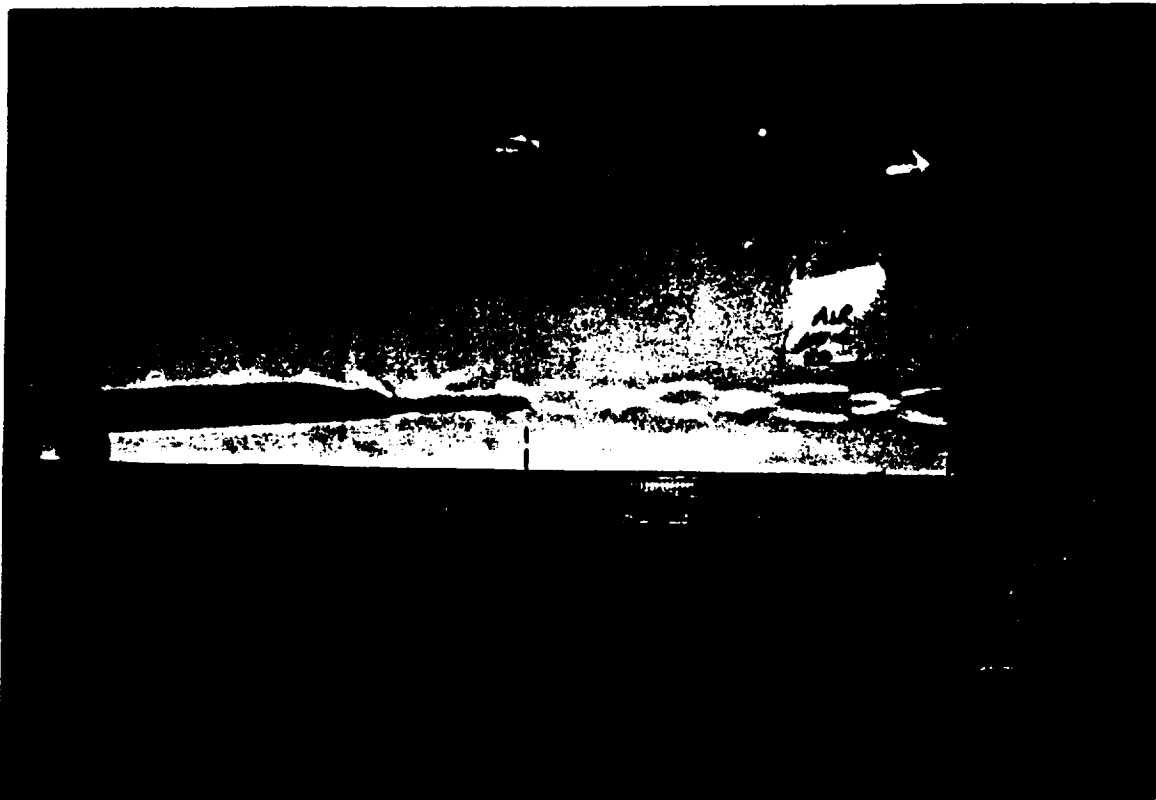
The flow is two-phased flow of air-water mixture. In Fig. 3, shadowgraph of air and air-water flows from the nozzle can be seen. The qualitative observation of the flow can be described as follows:

1. At exit plane temperature of the flow seem to fall suddenly to a very low temperature from its initial temperature which can be taken as tank temperature. While moving away from the nozzle, it rises to be in equilibrium with ambient temperature.
2. No water droplets or ice-droplet are found if the jet stream of the nozzle is not interrupted by any object.
3. When an obstacle is placed in the stream, more condensation seems to occur at an axial distance greater than 10 cm as compared to the smaller ones.
4. Best working distance seems to be 30 to 80 millimeters from the exit plane.

## 3. Literature Survey

The Literature Survey<sup>3</sup> revealed that most of theoretical and experimental studies reported in various journal were for subsonic fluid flows of the two-phased flow which are of interest to many industrial applications. However, the Anemometry and particle sizing are routinely done around in few high-speed wind tunnel experiments in aeronautical/aerospace research. These measurements are normally involved highly complex, expensive, and non portable custom-made equipment. This include Laser Doppler Anemometers, specially designed pitot probes, etc. It was observed that the measurement of the flow parameters such as, speed, direction, particle size, turbulence, vorticity, temperature etc in supersonic range put theoretical restrictions to the assumptions under which these parameters are measured in subsonic range by the conventional instruments.

In this project, we looked for low-cost equipment and experimental methods which could be easily available and provide us the required data within the given time frame of the project. Following sections of this technical report describes the methods which were adopted for the purpose.



(a)



(b)

Figure 3 Shadowgraphs of supersonic flow of the nozzle at 300 psig. The pitot probe and linear scale can also be seen. (a) for breathing air, (b) for air-water mixture.

## 4. Measurement of Supersonic Flow Velocity

The velocity of the nozzle stream in supersonic regime can be measured simply by a pitot probe, hot-wire/hot-film anemometer probe, Laser Doppler Anemometer(LDA), or by Laser transit Anemometry. In this project we have used pitot probe and Laser Transit Anemometer to measure supersonic velocity  $U_x$  at an axial distance  $x$  from the exit plane.

### 4.1 By Pitot Probe

A pitot probe is a tube with a blunt end facing into the airstream. A typical pitot probe has an inside to outside diameter ratio of 1/2 to 3/4, and a length of 15 to 20 diameters that is aligned with the airstream. Pitot probes are easy to construct and gives quite reliable measurements. It is an absolute measurement device which does not require calibration. Though the device is intrusive to the fluid flow, it is considered suitable because only one dimensional velocity data is required for this project. Fig. 4(a) shows the dimensions of the pitot probe which was designed and built at PF&C.

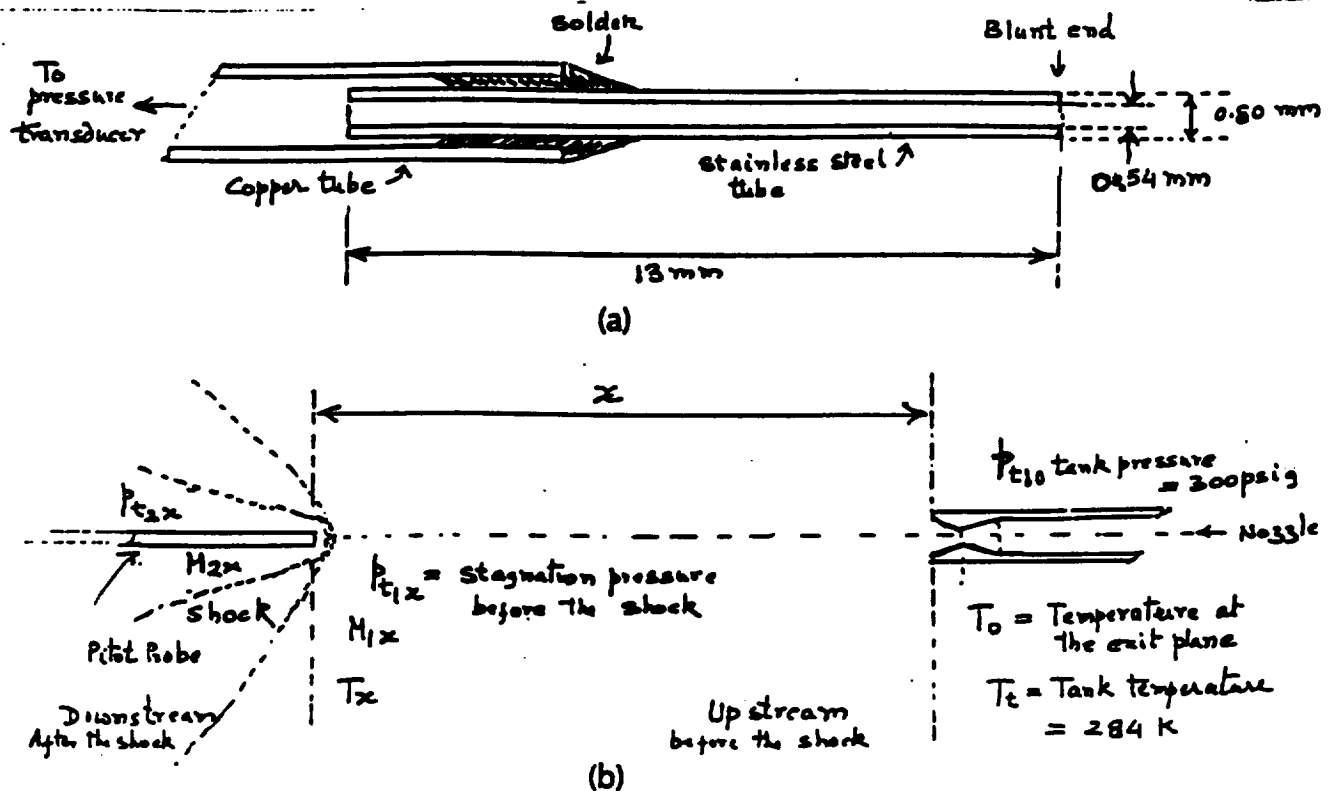


Figure 4 (a) dimensions of the Pitot Probe, (b) schematic diagram showing various flow parameters

An open-ended tube facing into the stream always measures the stagnation pressure it sees. Above  $M=1.0$  the shock wave that forms ahead of the tube means that it sees not the free stream stagnation pressure but the stagnation pressure behind a normal shock. The new value is called *pitot pressure*. In Fig. 3 a typical shock wave can be seen in the shadowgraph of the flow when pitot probe was aligned with the stream for the measurement.

#### 4.1.1 Calculation of the Mean Flow Velocity using Pitot Probe

Using theory of compressible fluids it can be shown<sup>4</sup> that

$$\frac{p_{t2x}}{p_{t1x}} = \left[ \frac{(\gamma-1)}{2\gamma M_{1x}^2 - (\gamma-1)} \right]^{\frac{1}{\gamma-1}} \left[ \frac{(\gamma+1) M_{1x}^2}{(\gamma-1) M_{1x}^2 + 2} \right]^{\frac{\gamma}{\gamma-1}} \quad (1)$$

Where  $p_{t2x}$ ,  $p_{t1x}$ ,  $T_x$ , and  $T_t$  are defined in Fig. 4 (b). This dimensionless ratio can be found in the Standard table<sup>5</sup> for the range  $1 \leq M_{1x} \leq 10$ .

Using this table value of  $M_{1x}$  can be determined for each value of stagnation pressure ratio measured at axial distance  $x$ . These values are listed in column 10 of the Table 1.

Similarly, if  $T_x$  is defined the temperature at a distance  $x$  from the exit plane and  $T_t$  is the fluid temperature inside the tank, it can shown that

$$\frac{T_x}{T_t} = \left[ 1 + \frac{(\gamma-1)}{2} M_{1x}^2 \right]^{-1} \quad (2)$$

by substituting the value of  $M_{1x}$  obtained by equation(1) into equation(2), temperature  $T_x$  of the supersonic flow can be determined at the measured axial distances  $x$ . These values are presented in column 12 of the Table 1.

In compressible fluid medium the speed of sound at an axial distance  $x$  is given by,

$$a_x = \sqrt{\gamma \cdot R_1 \cdot T_x} \quad (3)$$

where  $\gamma = 1.4$   
 $R_1 = 287.0 \text{ J/kg. K}$  ( gas constant )

Using equation(3) speed of sound  $a_x$  can be found for every  $x$  set experimentally. These values are shown in column 13 of the Table 1.

Finally the supersonic velocity of the flow can be calculated by equation(4) given below,

$$U_x = a_x \cdot M_x \quad (4)$$

These values are given in column 14 of the Table 1. Fig. 5 depicts the variation of the velocity of nozzle flow both for breathing air and air-water mixture.

**Table 1 Measurement of Pitot Pressure and Calculation  
of the Flow Velocity of the Supersonic Nozzle**

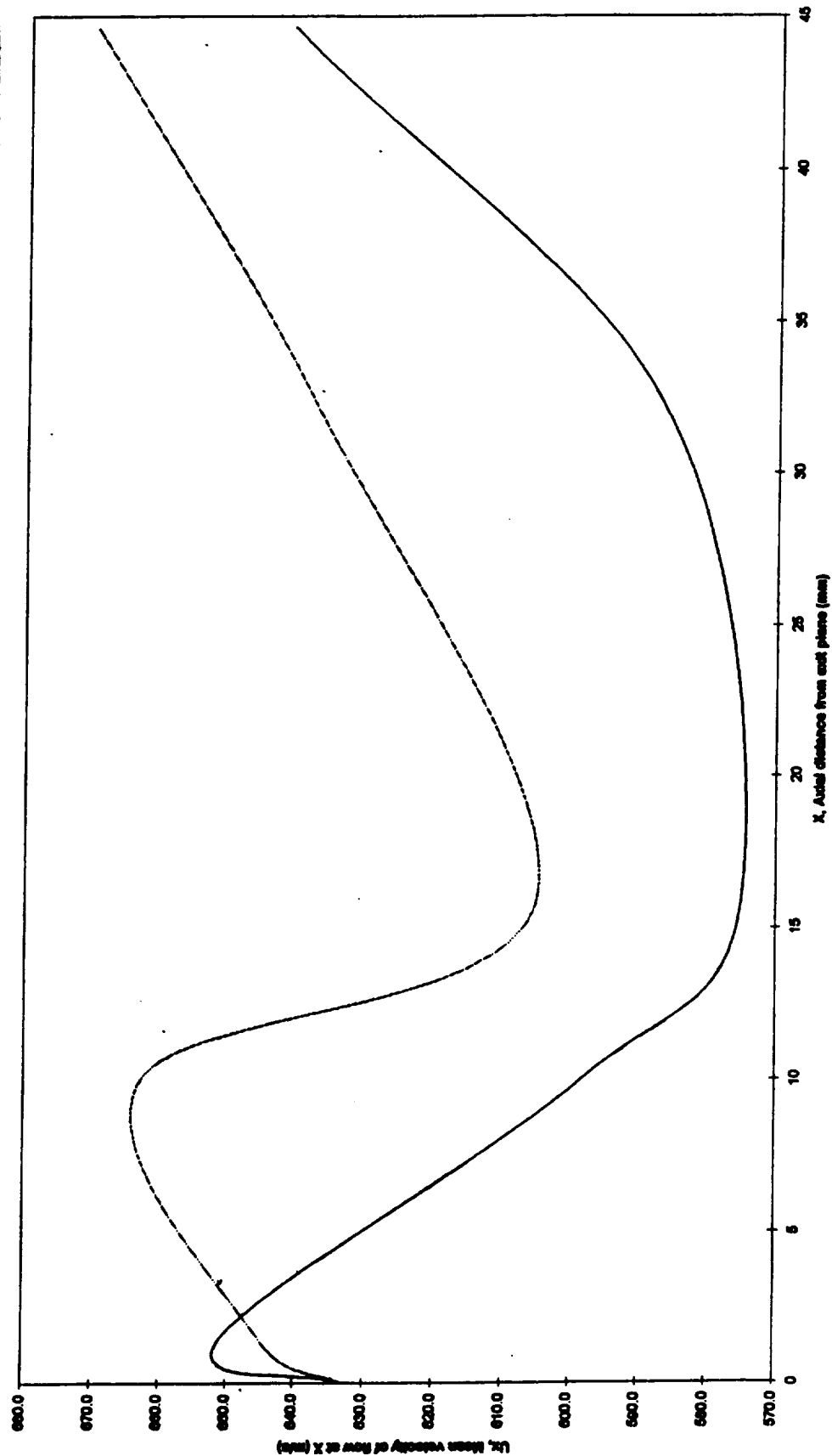
( Tank Pressure 300 psig, and Tank Temperature 284 K )

SERIAL NO.	MEDIUM	DISTANCE OF PROBE FROM EXIT PLANE		OUTPUT VOLTAGE OF THE PRESSURE TRANSDUCER		STAGNATION PRESSURE		RATIO	MACH NO.	RATIO	TEMPERATURE		VEL. OF SOUND)	Ux m/s
		(SHADOW) mm	(ACTUAL) mm	% F.S.	(VDC)	DOWNSTREAM (PSI)	UPSTREAM (PSI)				Tx	(K)		
1	Air	0	0	22.5	2.25	67.5	300	0.225	3.45	0.285	63.8	63.8	183.5	633.0
2	Air + Water	0	0	22.5	2.25	67.5	300	0.225	3.45	0.285	63.8	63.8	183.5	633.0
3	Air	4	1.5	16.5	1.65	49.5	300	0.165	3.8	0.257	73.0	73.0	171.3	660.8
4	Air + Water	4	1.5	16.1	1.61	54.3	300	0.181	3.69	0.266	76.1	76.1	174.9	645.3
5	Air	26	10	35	3.5	106	300	0.35	2.9	0.373	106.9	106.9	206.3	596.3
6	Air + Water	26	10	12.8	1.28	36.4	300	0.128	4.1	0.229	66.0	66.0	161.7	602.8
7	Air	41	15.6	45	4.5	135	300	0.45	2.63	0.419	119.0	119.0	218.7	575.1
8	Air + Water	41	15.6	33.4	3.34	100.2	300	0.334	2.99	0.359	102.0	102.0	202.4	605.2
9	Air	63	31.9	40.6	4.06	121.8	300	0.406	2.76	0.395	112.2	112.2	212.3	566.0
10	Air + Water	63	31.9	21.2	2.12	63.6	300	0.212	3.5	0.29	82.4	82.4	181.9	636.7
11	Air	116	44.6	19.4	1.94	56.2	300	0.194	3.6	0.278	79.0	79.0	178.1	641.2
12	Air + Water	116	44.6	10.6	1.06	31.8	300	0.106	4.3	0.213	60.5	60.5	155.9	670.4
13	Air	175	67.3	7.5	0.75	22.5	300	0.075	n/a	n/a				
14	Air + Water	175	67.3	7	0.7	21	300	0.07	n/a	n/a				



**Figure 5 Variation of The Flow  $U_x$  of the Supersonic Nozzle  
with respect to axial distance  $x$ ,  
for Air and Air-Water mixture**

( Tank Pressure 300 psig, and Tank Temperature 284 K )



—  $U_x$ , Air  
- - -  $U_x$ , Air + Water

## 4.2 By Laser Transit Anemometry

Laser Transit Anemometry(LTA) is based on the direct measurement of the transit times of seed particles in the flow as they cross the foci of a pair of laser beams (Fig. 6). The transit time of an individual particle,  $\tau_i$ , in conjunction with the known beam separation,  $s$ , provides a measurement of the velocity magnitude,  $v_i$ , of particle given by

$$v_i = s/\tau_i \quad (5)$$

The beams are rotated about an axis equidistant from and parallel to the two beams, enabling various beam orientations to be set with respect to the flow field.

To detect particles as they traverse the foci of the instrument, scattered light from individual particles is detected by two photomultiplier tubes(Fig. 7) connected to filter-discriminator / pulse-center detector circuits. As particles pass through the sample volume, pulses are produced on two separate channels, one for each beam. The method used to extract transit time information consists of computing the discrete cross correlation function in real time,  $r_{12}(i)$ , between the input pulse streams occurring on the two channels,  $P_1(t)$  and  $P_2(t)$ . This discrete correlation function is given by

$$r_{12}(\tau) = \sum_{i=0}^{\infty} P_1(t_i) P_2(t_i + \tau) \quad (6)$$

and is represented by as correlogram with 256 "bins" (or channels) with each successive bin representing a delay time  $\tau = i \Delta\tau$ .

In practice, turbulent fluctuations of the flow vector at the measurement point results in the LTA missing the particles passing out side the acceptance angle defined by the beam diameters and separation. Therefore, LTA data acquisitions performed by orienting the two beams at up to fifteen different angles with respect to the estimated mean flow direction and computing the correlogram using equation (2) at each angle. In this way an ensemble of correlograms in the  $(\tau, \alpha)$  domain representing slices through the flow field is generated and can be analyzed to yield the desired flow parameters. In the experiments conducted at Langley for this project, only one angle was considered which gave the best correlogram. ( $\alpha = 241.000$ ).

### 4.2.1 The LTA system

The LTA system which was used for the project at Langley is a Model 104, of Spectron Development Laboratories, Inc. It is a microcomputer based system (Fig. 8) in which LTA system control, data acquisition and data processing is performed by dedicated microprocessor based sub-systems. The optical system, xyuv drive, prototype nozzle, focusing Laser beams can be seen in photograph of Fig. 9 and two foci of Argon ion laser beams can be seen in the photograph of Fig. 10.

# LTA Sample Volume Geometry

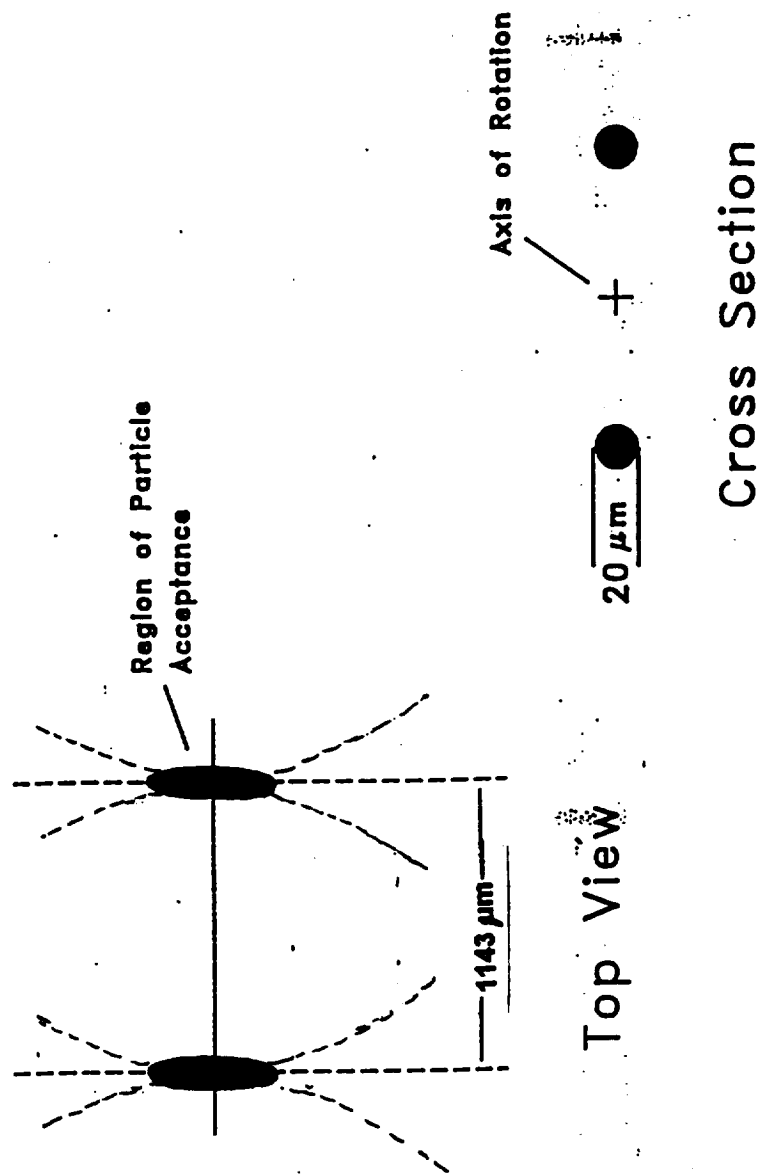


Figure 6 LTA Sample Volume Geometry

## LTA Optical Head Schematic

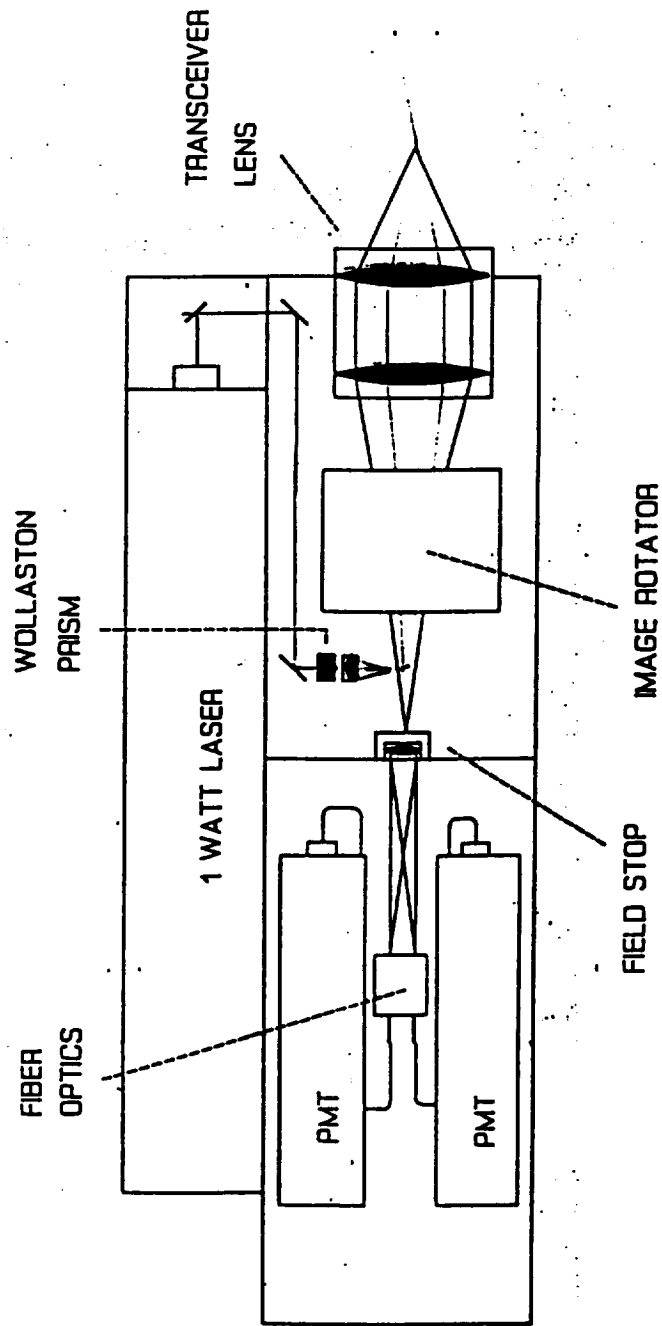


Figure 7 LTA Optical Head Schematic



Figure 8 Microcomputer based LTA system

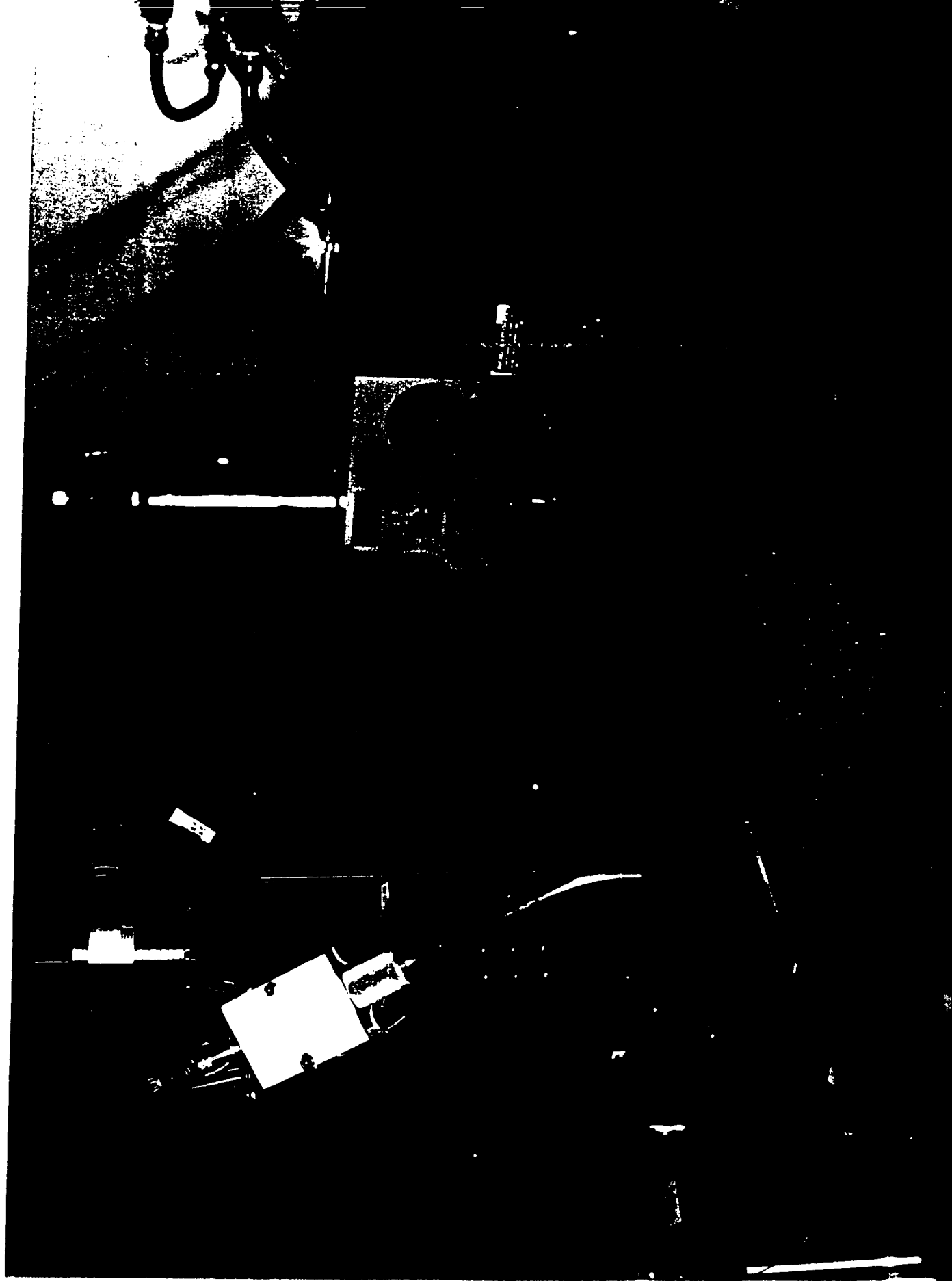


Figure 9 General Experimental set up at NASA/Langley Research Center



**Figure 10** Nozzle flow and foci of two Argon ion Laser beams

#### 4.2.2 Results of the LTA Measurements

A typical correlogram (one of the 53 computer outputs) is shown in Fig. 11. The mean velocity of the flow versus distance for supersonic gas-liquid nozzle is shown in Fig. 12. Variation of mean velocity with respect to distance was observed for tank pressures 220, 320, and 420 psig.

### 5. Measurements of Mass Rates of Water Droplets

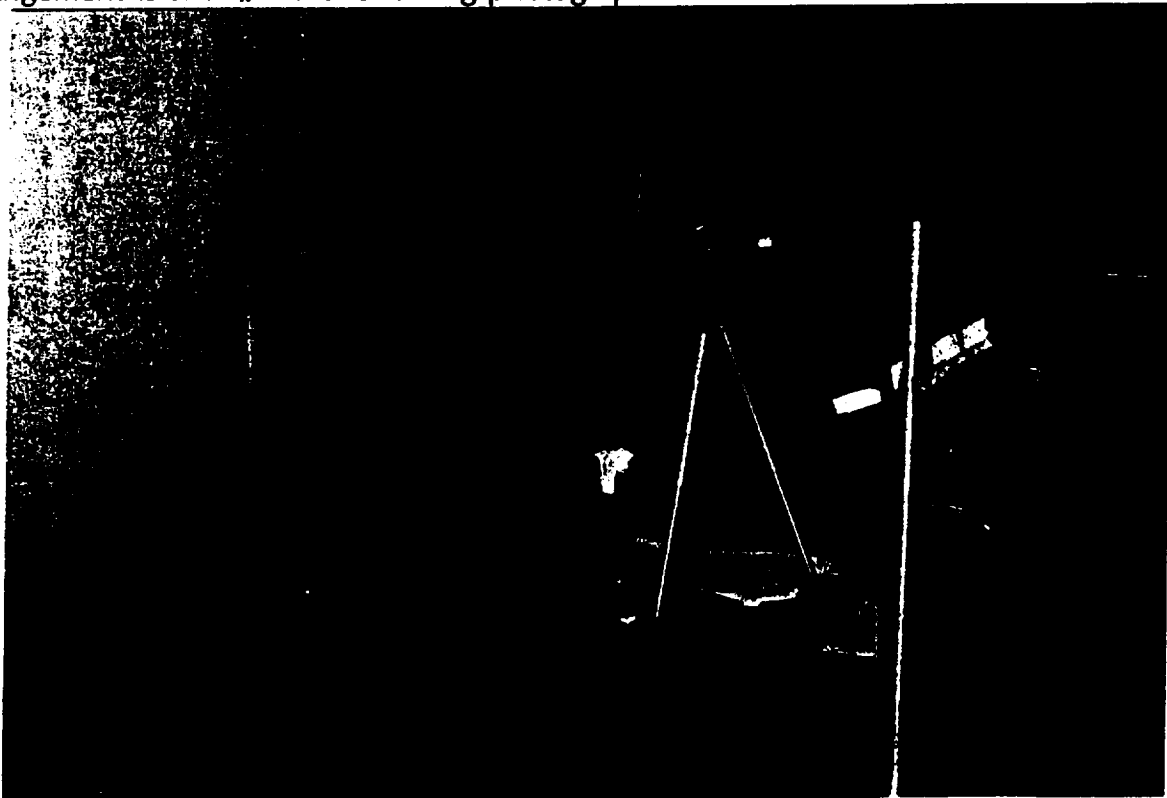
The flow of air-water mixture is obtained by the prototype control panel shown schematically in Fig. 1 and actually in Fig. 9. A very small amount of water is continuously mixed with compressed air before emerging out from the nozzle under differential pressure of 20 psig. The differential pressures are obtained by separate orifices shown in Fig. 1.

To order to assist the calculation of percentage content of water droplets in the supersonic flow of air-water mixture following observations were made:

1. At the tank pressure of 420 psig, 5 liters of water took 90 minutes to pass through the nozzle with uniform rate. This gives flow rate of water droplets 0.926 grams per second.
2. At the tank pressure of 320 psig, 4 liters of water took 77 minutes to pass through the nozzle with uniform rate. This gives flow rate of water droplets 0.866 grams per second.

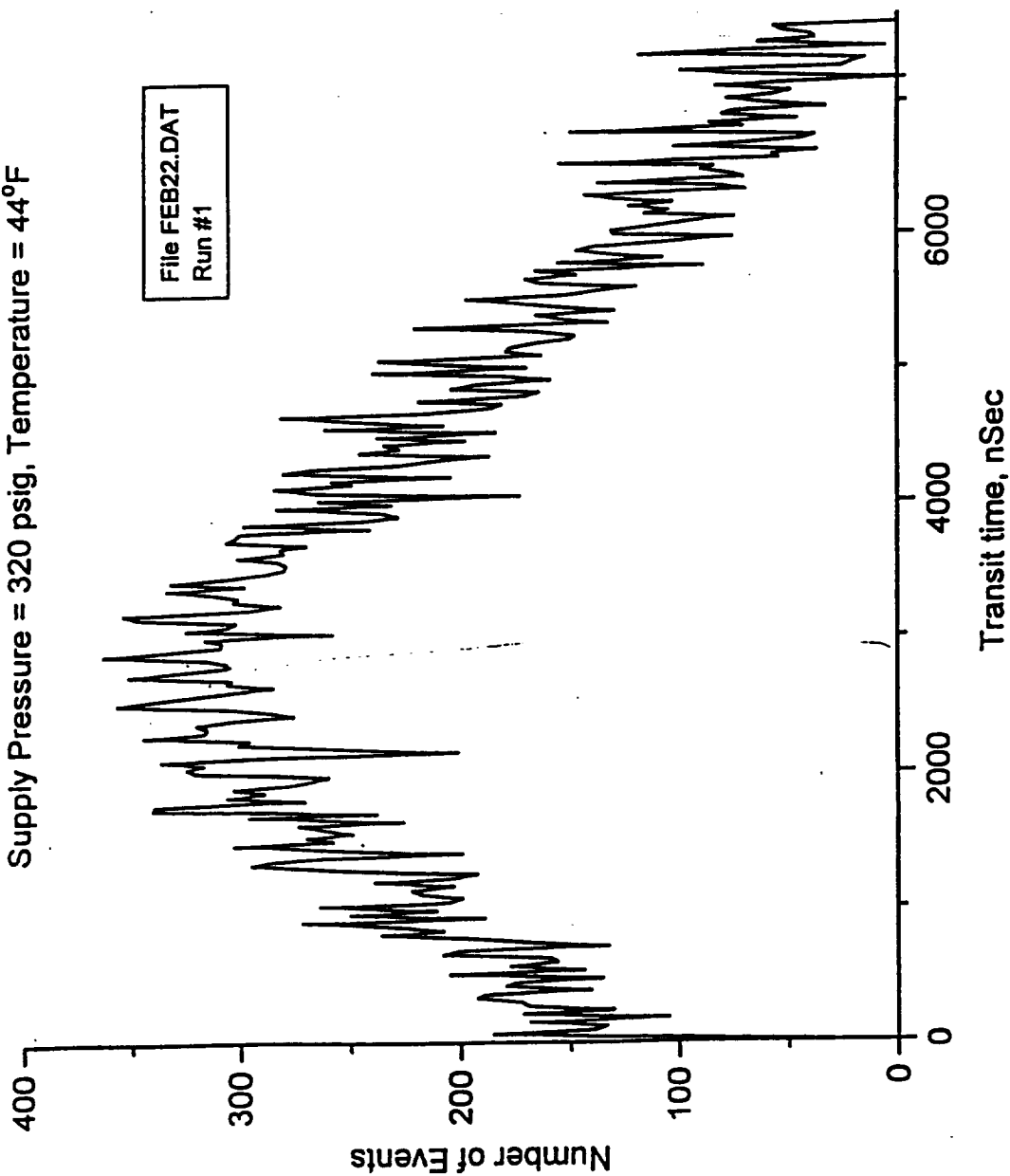
### 6. Visualization of the Flow

Visualization of the flow was done by shadow graph method. The experimental arrangement is shown in the following photograph.





KSC Cleaning Nozzle - LTA Measurements  
Supply Pressure = 320 psig, Temperature = 44°F



**Figure 11** A typical Correlogram of LTA system for calculation of mean velocity of the nozzle flow

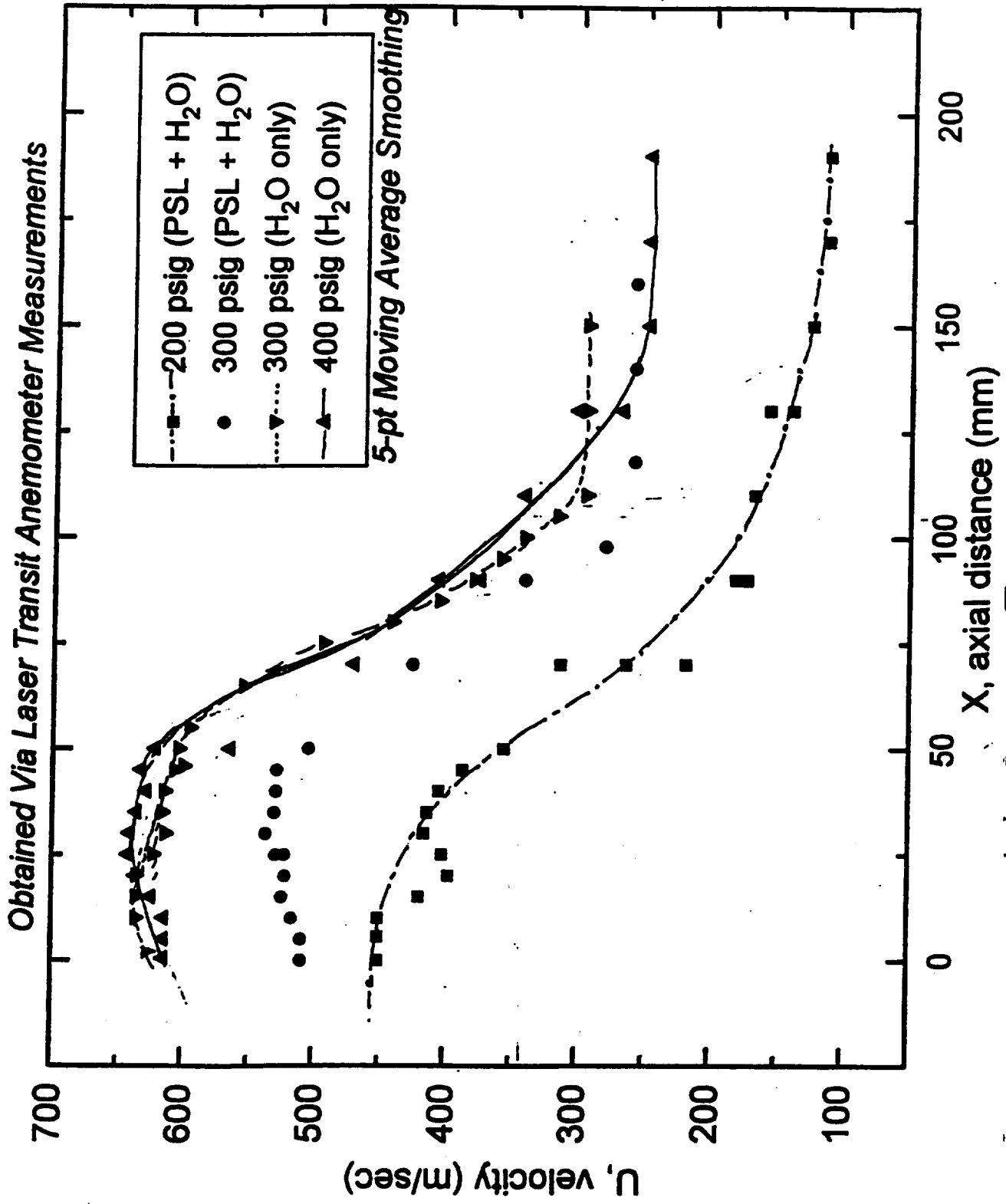


Figure 12 Mean Velocity versus Axial Distance for Supersonic Gas-Liquid Nozzle

## 7. Minimum size of the Water Droplets

The LTA experiments at Langley gave a quasi-quantitative conclusion about the average size of water droplets in the supersonic flow of the nozzle. Considering the 'Mean Velocity versus Axial Distance' curve for 320 psig tank pressure shown in Fig. 12. When 5 cc of 0.8 micron size polystyrene latex (PSL) particles is mixed with the water, the curve with lesser velocity was obtained (depicted by round dots). This drop in the velocity of flow indicates that particles are heavier than the in flow obtained without PSL. This means water droplet size is much smaller than 0.8 micron.

## 8. Concluding Remarks

Mean velocity of the nozzle remains almost constant up to axial distance of 50 mm (2 inches). It was observed that increasing the tank pressure increases the mean velocity of the flow at the exit of the nozzle. The optimum tank pressure, however, seems to be around 300 psig. Best working distance seems to be between 30 to 80 millimeters. The best operating distance can be confirmed by the theoretical model of the flow.

## 9. Acknowledgements

Thanks are extended to Dr. William M. Humphreys Jr (Laser Velocity Section) for his valuable help given to us in collecting LTA data and Dr J. Meyers for providing all the facilities at NASA Langley's Instrument Research Division. Thanks to all the members of the SGLCS project for their suggestions and cooperation.

## 10. References

1. TRDA Announcement of Opportunity, January 1994
2. Caimi, R. E. B., Thaxton, E. A., "Supersonic Gas-Liquid Cleaning System", Fourth National Technology Transfer Conference and Exposition, Vol. 1, Feb. 1994.
3. Please see the appendix 'A' of this report
4. Alan Pope, Kenneth L. Goin; 'High Speed Wind Tunnel Testing'; pp 12-21

# Appendix 'A'

## Literature Survey

Following Journals and Technical Literature were scanned to search relevant information (direct/ indirect) which may help in selecting appropriate method(s) and adopting most suitable experimental procedure(s) to be used in the project, to measure velocity and particle size distribution in the stream of supersonic flow of breathing air and also of breathing air mixed with 0.01% of water, coming out from the proto-type nozzle.

- [A] Review of Scientific Instruments
- [B] Applied Optics
- [C] AIAA Journal
- [D] Measurement Science and Technology
- [E] Books and Conference Proceedings
- [F] Technical Information from the Instrument manufacturers
- [G] Technical Reports, Press Release and others

[A] REV. OF SCIENTIFIC INSTRUMENTS, Vols. 54 - 64, 1983 - 93 + current issues.

### 44.60 Thermodynamic processes (phenomenology, experimental techniques)

Ring wire anemometer—Part I: Calibrations and cooling laws. - Jean-Paul Giovanangeli, Pierre Chambaud, and Patrice Mestayer; 58 (11), 2172-4 (1987)

Ring wire anemometer—Part II: Measurement of small scale turbulence. - Patrice Mestayer, Jean-Paul Giovanangeli, and Pierre Chambaud; 58 (11), 2175-80 (1987)

### 47.27 Turbulent flows, convection, and heat transfer

Density measurements of a pulsed supersonic gas jet using nuclear scattering. - J. G. Pronko, D. Kohler, I.v. Chapman, T.T. Bardin, P.C. Filbert, and J. D. Hawley; 64(10), 2947-51.

### 47.40.K Supersonic and hypersonic flows

Comparison between constant-current and constant-temperature hot-wire anemometers in high-speed flows. - D. Bestion, J. Gaviglio, and J. P. Bonnet; 54 (11), 1513-24(1983)

Velocity distribution of supersonic nozzle beams. - H. Haberland, U. Buck, and M. Tolle; 56(9), 1712-6 (1985)

### 47.55.E Nozzles

Velocity distribution of supersonic nozzle beams. - H. Haberland, U. Buck, and M. Tolle; 56 (9), 1712-6 (1985)

Experimental study of a hot wire, sonic nozzle probe for concentration measurements  
Damien Maroteaux, Fadia Maroteaux, and Michel Murat; 62 (4), 1057-62 (1991)

#### 47.60 Flows in ducts, channels, and conduits

Velocity visualization in gas flows using laser-induced phosphorescence of biacetyl.

- B. Hiller, R. A. Booman, C. Hassa, and R. K. Hanson; 55 (12), 1964-7 (1984)

Curved-tube flowmeter. - H. Joutman; 56 (12), 2295-8 (1985)

Aeroacoustic flow sensor. - P. Shakkattai, E. Y. Kwack, and L. H. Back; 62 (9), 2205-12 (1991)

#### 47.80 Instrumentation for fluid dynamics

Comparison between constant-current and constant-temperature hot-wire anemometers in high speed flows. - D. Bestion, J. Gaviglio, and J. P. Bonnet; 54 (11), 1513-24 (1983)

Calibration of a three-element hot-wire anemometer. - G. T. Skinner and W. J. Rae; 55 (4), 578-81 (1984)

Laser Doppler velocimeter for multicomponent measurement using an electro-optical modulator demonstrated for a two-component optical configuration. - R. H. Bahnen and K. H. Koeller; 55 (7), 1090-3 (1984)

Particle discrimination and background suppression in photon-correlation laser velocimetry. - Todd D. Fansler; 55 (10), 1556-63 (1984)

Velocity visualization in gas flows using laser-induced phosphorescence of biacetyl. - B. Hiller, R. A. Booman, C. Hassa, and R. K. Hanson; 55 (12), 1964-7 (1984)

Laser Doppler velocimetry using polarization-preserving optical fibers for simultaneous measurement of multidimensional velocity components. - Noboru Nakatani, Munëo Tokita, Takao Izumi, and Tomoharu Yamada; 56 (11), 2025-9 (1985)

Ring wire anemometer—Part I: Calibrations and cooling laws. -Jean-Paul Giovanangeli, Pierre Chambaud, and Patrice Mestayer; 58 (11), 2172-4 (1987)

Ring wire anemometer—Part II: Measurement of small-scale turbulence. - Patrice Mestayer, Jean-Paul Giovanangeli, and Pierre Chambaud; 58 (11), 2175-80 (1987)

Dedicated microprocessor system to control laser Doppler velocimetry measurements and to reduce data. - D.V. Srikantiah, T. Philip, and W. W. Wilson; 59 (5), 793-6 (1988)

Signal generator for stimulation of laser doppler velocimetry experiments.- J. C. Amare and M.A. Robolledo; 60 (5), 939-42 (1989)

Determination of the magnitudes and signs of flow parameters by hot-wire anemometry. Part I. Measurements using hot-wire X probes. - Michael Acrivelllis; 60 (7), 1281-5 (1989)

Determination of the magnitudes and signs of flow parameters by hot-wire anemometry. Part II. Measurements using a triple hot-wire probe. - Michael Acrivelllis; 60 (7), 1281-5 (1989)

Pilot tube as a calibration device for turbulence measurement. - Sadek Z. Kassab; 61(6), 1757-9 (L) (1990)

Experimental study of a hot wire, sonic nozzle probe for concentration measurements. - damien Maroteaus, Fadila Maroteaus, and Michel Murat; 62 (4), 1057-62 (1991)

21

A fast-response microthermocouple. - P. Beckman, R. P. Roy, K. Whitfield, and A. Hasan; 64 (10), 2947-51 (1993)

**[B] APPLIED OPTICS, Vols. 11 - 32 + current issues:**

Measurement of Particle size, Number Density, and Velocity Using a Laser Interferometer. W. M. Farmer; 110, 2603-12 (1972)

Sample space for particle size and velocity measuring interferometers. W. M. Farmer; 15, 1984-89 (1976)

Two optical methods for simultaneous measurement of particle size, velocity, and refractive index. Amir Naqwi, Franz Durst, and Xiaozhi Lui; 30, 4949-59 (1991)

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**SUPERSONIC GAS LIQUID CLEANING SYSTEM**

**REPORT OF WORK CONDUCTED BY**

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**FOR**

**TECHNOLOGICAL RESEARCH AND DEVELOPMENT AUTHORITY (TRDA)  
6750 SOUTH HIGHWAY U.S. 1  
TITUSVILLE, FL 32780**

**IN CAPACITY AS SUBCONTRACTOR TO**

**BETHUNE-COOKMAN COLLEGE  
DAYTONA BEACH, FL 32115**

**UNDER**

**TRDA GRANT #411**

**PRINCIPAL INVESTIGATOR**

**L.L. NARAYANASWAMI**

## INTRODUCTION

This report is submitted by Embry-Riddle Aeronautical University (ERAU) to Bethune Cookman College (BCC), and describes the work performed under TRDA Grant #411 towards the development of a Supersonic Gas-Liquid Cleaning System. Commercial cleaning systems currently in use utilize the chemical action of a solvent to remove contaminants from the surface being cleaned. A vast majority of these systems utilize CFC-113 as the solvent. Due to its detrimental effect on the earth's ozone layer, there is a major effort worldwide to eliminate the use of CFC-113 as much as possible. The development of the supersonic gas-liquid cleaning system is an effort in this direction.

The supersonic gas-liquid cleaning system is shown in schematic in Figure 1.

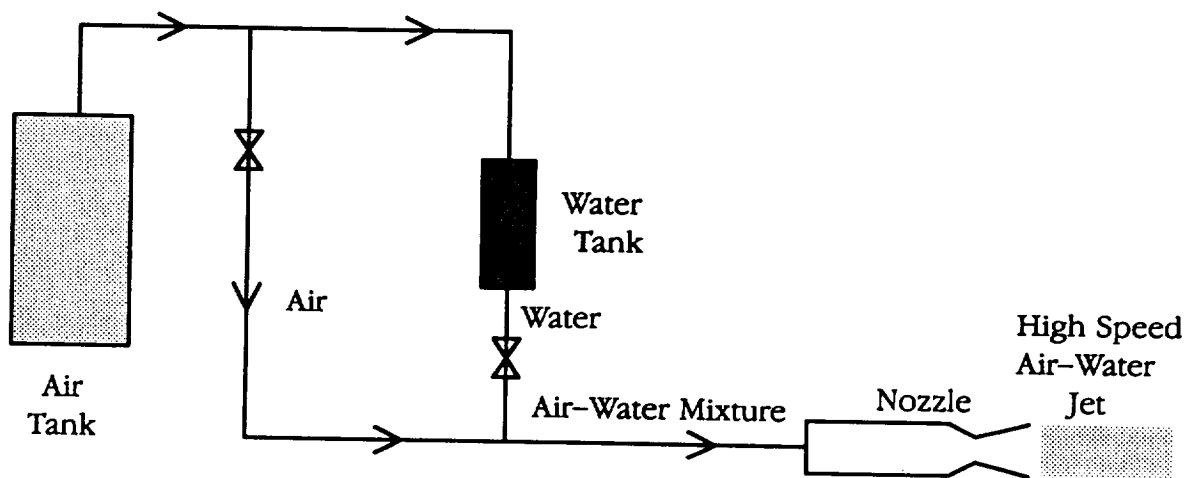


Figure 1: Schematic of Supersonic Gas-Liquid Cleaning System

It consists of a pressurized gas supply and a water supply. Gas leaves its tank through two pipelines. In one line, the gas passes through pressure-regulating valves and flows into a converging-diverging nozzle. The gas passing through the second line flows into the water tank, and forces the water into the pipeline. This results in the flow of a mixture of gas and water through the nozzle. Due to the drop in pressure through the nozzle, water is atomized into droplets as it flows towards the nozzle exit. Furthermore, the momentum interaction between the gases and the water results in the latter leaving the nozzle at a high speed. The impingement of this high-velocity jet of "heavy" water droplets has the potential for cleaning surfaces by "impact."

Limited testing of the system illustrated in Figure 1 was carried out at NASA-KSC.<sup>1</sup> In one of these tests, the system was used on an already precision-cleaned surface with a view to flushing out and capturing the residual contaminants on it. The flush was then analyzed to determine the concentration of the residual contaminants. Results were a measure of the cleaning capability of the original precision cleaning process used on the surface. In other words, the gas-liquid cleaning system was used as a tool for the "verification" of the

effectiveness of the precision-cleaning process. The tests indicated that the system was a viable alternative to CFC-based "verification" methods.

The success of the gas-liquid cleaning system as a "verification" tool naturally led to its consideration as a primary cleaning device. The first step in this process was to determine conditions that would be optimum for cleaning purposes. Accordingly, a two-phase flow model was applied to the nozzle.<sup>2</sup> In this analysis, the two phases were assumed to be thermal equilibrium with one another throughout the nozzle. Additional modeling work was done at University of Florida.<sup>3</sup>

The current program of work was initiated to extend the limited experimental and modeling work mentioned above. The work was divided into two segments. BCC conducted experimental studies with the system, and ERAU was involved in the development of a theoretical model to characterize the flow through the nozzle.

One of the earliest investigations of two-phase nozzle flows was carried out by Hultberg and co-workers.<sup>4</sup> The investigators developed a model, and tested it by comparing the results with those from an experimental program specifically designed for the investigation. Other investigators had also been involved in the study of two-phase nozzle flows. The work of Reference 5 was concerned with the behavior of large water droplets in high speed flow. Both theoretical and experimental studies were performed as part of this effort. The investigation of Reference 6 was concerned with the development of a model describing two-phase flow through a nozzle. The model considered droplet breakup, and momentum and energy transport between phases. The model was subsequently used to perform parametric studies. The model results were tested against experimental data as well. One other two-phase investigation that could be mentioned here was the one performed by Marble.<sup>7</sup> This work was directed at the study and optimization of two phase flows in rocket motor nozzles.

All the four investigations cited in the last paragraph modeled the nozzle flow as one dimensional. More recently, several multi-dimensional models have been developed. Shih-Chang has developed an axisymmetric model<sup>8</sup> and a three-dimensional model<sup>9</sup> describing two-phase nozzle flows. Other investigators have also developed multi-dimensional models.<sup>10,11</sup>

While it would have been worthwhile to develop a multi-dimensional model accounting for droplet breakup, the short duration of the project precluded such an effort. Thus, the model developed for this work was one-dimensional, and did not account for droplet breakup. The subsequent sections of the report describe model development, methodology developed for solving the model equations, and comparison of the results with experimental observations.

## NOZZLE MODEL DESCRIPTION

The model described in what follows describes a two-phase flow through a converging-diverging nozzle of a given geometry. The development closely follows that in Reference 4. The model is based on the following assumptions: (1) the flow is steady and one-dimensional, (2) droplets are uniformly distributed in the mixture, (3) droplets are uniform in diameter, and have uniform properties, (4) drag between the gas and liquid phases can be described in terms of a mean velocity difference between them, (5) heat transfer between the phases can be related to the mean temperature difference between them and (6) there is no mass transfer between phases.

Subject to these assumptions, the following equations can be used to describe the two phase flow:

$$\text{Mass (Gas Phase):} \quad \rho u A = \dot{m} \quad (1)$$

$$\text{Mass (Particle Phase):} \quad \rho_p u_p A = \kappa \dot{m} \quad (2)$$

$$\text{Momentum (Gas Phase):} \quad \rho u \frac{du}{dx} + \frac{dp}{dx} = F_p \quad (3)$$

$$\text{Momentum (Particle Phase):} \quad \rho_p u_p \frac{du_p}{dx} = -F_p \quad (4)$$

$$\text{Energy (Gas Phase):} \quad \rho u C_p \frac{dT}{dx} - u \frac{dp}{dx} = (u_p - u) F_p + Q_p \quad (5)$$

$$\text{Energy (Particle Phase):} \quad \rho_p u_p C_w \frac{dT_p}{dx} = -Q_p \quad (6)$$

In the above equations,  $\rho$  and  $\rho_p$  represent the densities of the gas- and particle-clouds,  $u$  and  $u_p$  denote the gas and particle velocities,  $T$  and  $T_p$  represent the gas and particle temperatures, and  $p$  is the pressure.  $\dot{m}$  and  $\kappa \dot{m}$  denote the gas and particle mass flow rates, and  $C_p$  and  $C_w$  are the gas and particle constant pressure specific heats. Utilizing assumptions (4) and (5), the drag force  $F_p$  and the heat transfer  $Q_p$  between the phases can be written as

$$\text{Drag :} \quad F_p = f (u - u_p) \quad (7)$$

$$\text{Heat Transfer :} \quad Q_p = q (T - T_p) \quad (8)$$

where  $f$  and  $q$  are constants related to the gas and particle phase properties. Equations (3) and (4) may now be combined to get the overall momentum equation as follows:

$$\rho u \frac{du}{dx} + \rho_p u_p \frac{du_p}{dx} + \frac{dp}{dx} = 0 \quad (9)$$

Equations (5) and (6) could be used, in conjunction with Equations (3) and (4), to obtain the following overall energy equation:

$$(C_p T + \frac{u^2}{2}) + \kappa (C_w T_p + \frac{u_p^2}{2}) = \text{constant} \quad (10)$$

In the above equation, the constant can be determined by using the nozzle boundary conditions.

## NONDIMENSIONALIZING THE MODEL EQUATIONS

It is useful to nondimensionalize the equations governing the system. Accordingly, the various equations are nondimensionalized using reference variables  $p_0$ ,  $T_0$ ,  $\rho_0$ ,  $u_0$ ,  $L$  and  $(m/\rho_0 u_0)$ . In this list,  $p_0$  is the upstream tank pressure,  $T_0$  is the upstream tank temperature,  $\rho_0$  is the upstream tank density,  $u_0$  is  $\sqrt{2C_p T_0}$ , and  $L$  is the length of the nozzle. Thus, the equations are cast in terms of the following nondimensional variables:

$$\text{Normalized pressure } p^* = \frac{p}{p_0} \quad (11a)$$

$$\text{Normalized Gas Temperature } T^* = \frac{T}{T_0} \quad (11b)$$

$$\text{Normalized Particle Temperature } T_p^* = \frac{T_p}{T_0} \quad (11c)$$

$$\text{Normalized Gas Velocity } u^* = \frac{u}{u_0} \quad (11d)$$

$$\text{Normalized Particle Velocity } u_p^* = \frac{u_p}{u_0} \quad (11e)$$

$$\text{Normalized Area } A^* = \frac{A}{(\dot{m}/\rho_0 u_0)} \quad (11f)$$

$$\text{Normalized Length } x^* = \frac{x}{L} \quad (11g)$$

The normalized form of the equations are given below.

$$\text{Gas Mass : } p^* u^* A^* = T^* \quad (12)$$

$$\text{Particle Momentum : } u_p^* \frac{du_p^*}{dx^*} = C (u^* - u_p^*) \quad (13)$$

$$\text{Overall Momentum : } \frac{2 C_p}{R T^*} u^* \frac{du^*}{dx^*} + \frac{2 C_p}{R T^*} \kappa u^* \frac{du_p^*}{dx^*} + \frac{1}{p^*} \frac{dp^*}{dx^*} = 0 \quad (14)$$

$$\text{Particle Energy : } u_p^* \frac{dT_p^*}{dx^*} = D (T^* - T_p^*) \quad (15)$$

$$\text{Overall Energy : } T^* + u^{*2} + \kappa \frac{C_w}{C_p} T_p^* + \kappa u_p^{*2} = 1 + \kappa \frac{C_w}{C_p} \quad (16)$$

In the above set of equations, C and D are nondimensional equivalents of f and q, respectively, and are given by<sup>4,7</sup>

$$C = \frac{9}{2} \frac{\mu L}{\bar{\rho}_w \sigma^2 u_o}; \quad D = \frac{3kL}{C_w \sigma^2 \bar{\rho}_w u_o} \quad (17a \& b)$$

where  $\mu$  and  $k$  are, respectively, the coefficients of viscosity and thermal conductivity of the gas phase.  $\sigma$  is the particle radius, and  $\bar{\rho}_w$  is the density of the particle material. Further, it should be noted that the 'constant' on the right hand side of the dimensional form of the overall energy equation (Equation (10)) has been obtained by observing that, at the entrance to the nozzle from the tank ( $x^* = 0$ ),  $u^*$  and  $u_p^*$  are zero, and  $T^*$  and  $T_p^*$  are 1. This results in the 'constant' being evaluated to be  $(1 + \kappa C_s/C_p)$  as shown in Equation (16).

The five equations (12) through (16) describe the variation with  $x^*$  of six variables  $p^*$ ,  $T^*$ ,  $T_p^*$ ,  $u^*$ ,  $u_p^*$  and  $A^*$ . If the variation of one of these variables with  $x^*$  is known, then the five equations can be used to obtain the variation of the other five with respect to  $x^*$ . In particular, the flow properties at the exit plane of the nozzle can be obtained.

## INITIAL CALCULATIONS USING MODEL EQUATIONS

In order to verify the accuracy of the model equations, preliminary calculations were performed by assuming the gas velocity to be known through the nozzle. A simple variation, namely that  $u^*$  varies linearly with  $x^*$ , was assumed ( $u^* = \alpha x^*$ ). Then, Equations (12) through (16) were used to determine the variation of the other variables ( $T^*$ ,  $T_p^*$ ,  $u_p^*$  and  $A^*$ ) with  $x^*$ . The appropriate boundary conditions at the nozzle entrance ( $x^* = 0$ ) were  $p^* = 1$ , and, as mentioned in connection with Equation (16) above,  $u_p^* = 0$ ,  $T^* = 1$  and  $T_p^* = 1$ .

In performing these calculations, the following values were assumed for the several constants appearing in the model:  $D = 10.$ ,  $C = 100.$ ,  $C_p = 1004.5$  J/kg-K,  $C_w = 494$  J/kg-K,  $R = 287$  J/kg-K and  $\kappa = 0.3$ . In addition, the constant relating  $u^*$  to  $x^*$  (the quantity  $\alpha$  in  $u^* = \alpha x^*$ ) was taken to be 0.9. The results of the calculations are shown in Figure 2.

## SOLUTION FOR ARBITRARY AREA RATIOS

While the solution described in the previous section is useful as a reference operating characteristic, the variation of the gas velocity through the nozzle is not readily available in practical situations. More usually,  $A^*$  would be known as a function of  $x^*$ . Thus, it is necessary to develop a solution methodology that would utilize the model equations (Equations (12) through (16)) to determine the variation of  $u^*$ ,  $u_p^*$ ,  $T^*$ ,  $T_p^*$  and  $p^*$  with  $x^*$  for any arbitrary nozzle profile ( $A^*(x^*)$ ). The methodology is described in this section.

As a first step in obtaining the solution for arbitrary area ratios, the equations are written in a suitable form. The resulting equation set is presented below:

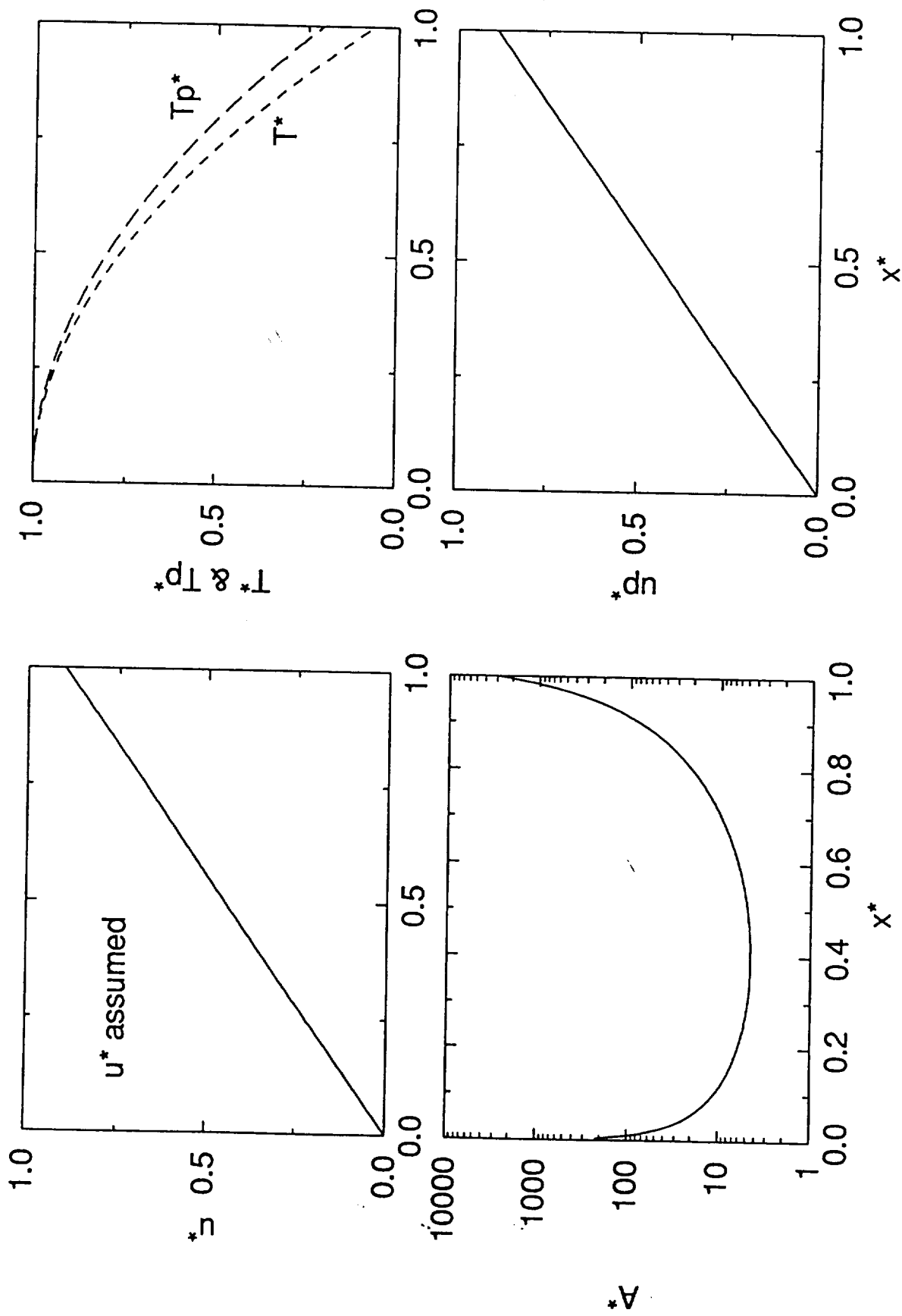


Figure 2: Solution for Linear Velocity Variation



$$u_p^* \frac{du_p^*}{dx^*} = C (u^* - u_p^*) \quad (13)$$

$$u_p^* \frac{dT_p^*}{dx^*} = D (T^* - T_p^*) \quad (15)$$

$$\frac{du^*}{dx^*} = \frac{-\frac{T^*}{A^*} \frac{dA^*}{dx^*} + \left( \frac{2C_p \kappa u^*}{R} - 2\kappa u_p^* \right) \frac{du_p^*}{dx^*} - \frac{\kappa C_w dT_p^*}{C_p dx^*}}{\frac{T^*}{u^*} - \frac{2C_p}{R} u^* + 2u^*} \quad (18)$$

$$T^* + u^{*2} + \kappa \frac{C_w}{C_p} T_p^* + \kappa u_p^{*2} = 1 + \kappa \frac{C_w}{C_p} \quad (16)$$

The above set of four equations ((13), (15), (16) and (18)) describes the variation of 5 variables ( $u_p^*$ ,  $T_p^*$ ,  $A^*$ ,  $T^*$ , and  $u^*$ ) with  $x^*$ , the distance along the nozzle. If the nozzle profile information ( $A^*(x^*)$ ) is known, the above set, in principle, can be solved to obtain the variation of the other four variables with  $x^*$  by making use of the boundary conditions at  $x^* = 0$ :

$$T^* = T_p^* = 1; u^* = M = u_p^* = 0 \quad (19)$$

Unfortunately, the integration cannot be started at  $x^*$  of zero, since  $A^*$  goes to infinity there. Consequently, an alternate solution has to be assumed over some initial distance in the nozzle. In this work, the linear gas velocity variation ( $u^* = \alpha x^*$ ), discussed elsewhere, is assumed over some initial nozzle length (say, from  $x^* = 0$  to  $x^* = 0.03$ ). This process would provide a set of boundary conditions at  $x = 0.03$ . The solution is then continued using the specified nozzle profile.

The value of  $\alpha$  cannot, however, be arbitrarily chosen since the earlier discussion with linear velocity profiles shows that a particular value of  $\alpha$  corresponds to a particular

nozzle profile (recall the particular  $A^*$  variation obtained with  $\alpha = 0.9$ , Figure 2). Thus, the value of  $\alpha$  has to be checked for correctness. If found to be incompatible with the specified nozzle profile, it has to be suitably corrected. This checking and correcting is performed at the nozzle throat, as described below.

It can be shown that the gas velocity  $u_t^*$  at the nozzle throat is given by the following analytical expression:<sup>4</sup>

$$u_t^{*2} = a_m^{*2} \left[ 1 + \kappa \frac{du_p^*}{du^*} \right]^{-1} \quad (20)$$

where  $a_m^*$  is the speed of sound in the mixture. This expression is obtained by noting that  $dA^*/dx^*$  is zero at the throat location of the nozzle. Thus, there are two (one from numerical solution and the other from Equation (20)) independent estimates of  $u^*$  at the nozzle throat location. The two values will agree if  $\alpha$  is correctly chosen. If they do not, a new value of  $\alpha$ ,  $\alpha_{new}$ , is obtained as

$$\alpha_{new} = \alpha_{old} + \delta\alpha; \quad \delta\alpha = \eta \frac{u_t^*_{Eqn.20} - u_t^*_{num}}{x_t^*} \quad (21)$$

where  $\eta$  is a constant, and  $x_t^*$  denotes the throat location.

A computer code in FORTRAN has been developed to carry out the solution method outlined above. The code utilizes an Ordinary Differential Equation Solver to carry out the necessary integration.

The solution technique for arbitrary area ratios was checked by applying it to the nozzle profile obtained by using the linear velocity variation. Accordingly, several linear velocity profiles were assumed ( $\alpha = 0.6, \alpha = 0.7, \alpha = 0.8, \alpha = 0.9$ ). For each of these cases, the nozzle area variation was obtained. These area variations were then used as inputs to the arbitrary area ratio method to determine if it predicted back the linear velocity variations.

In each of the cases tried, the method successfully predicted the correct linear velocity variations associated with the specified nozzle profiles. Table 1 below compares the values of  $\alpha$  obtained from this method with their correct values.

**TABLE 1: Comparison of  $\alpha_{act}$  and  $\alpha_{num}$**

$\alpha_{act}$	$\alpha_{num}$
0.9	0.901
0.8	0.798
0.7	0.695
0.6	0.599

It should be noted that, with linear velocity variation in the nozzle, the check-condition (Equation 20) can be shown to reduce to

$$u_t^{*2} = \frac{a_m^{*2}}{1 + \kappa \frac{\beta}{\alpha}} \quad (22)$$

$$\text{with } a_m^{*2} = \frac{R}{2C_p} \left( 1 + \alpha^2 x^{*2} \frac{C_p}{C_{eq}} \right), \quad (23)$$

$$\beta = \frac{1}{2} (\sqrt{C^2 + 4C\alpha} - C), \text{ and} \quad (24)$$

$$C_{eq} = C_p \left[ D \left( 1 + \frac{\kappa C_w}{C_p} \right) + 2\beta \right] \left( 1 + \kappa \frac{\beta^2}{\alpha^2} \right)^{-1} (D + 2\beta)^{-1} \quad (25)$$

Since the actual nozzle velocity variation is known to be linear in the test cases, Equation (22) has been used to determine the correct value of  $u_t^*$  required for updating the value of  $\alpha$  (Equation (21)).

It is appropriate, at this juncture, to mention another solution method tried during the course of this investigation. In this method,  $u^*$  was replaced by an auxiliary variable  $Z$ , defined as  $1/2(M^2-1)^2$ , where  $M$  is the Mach number based on the speed of sound in gas. The variation of  $Z$  with  $x^*$  is described by the following set of equations:

$$\begin{aligned} \frac{dZ}{dx^*} = & 2M^2 \left( \frac{1}{T^*} + \frac{u^{*2}}{T^{*2}} \right) \left[ \frac{T^*}{A^*} \frac{dA^*}{dx^*} - \left( \frac{2C_p \kappa u^*}{R} - 2\kappa u_p^* \right) \frac{du_p^*}{dx^*} \right. \\ & \left. + \frac{\kappa C_w}{C_p} \frac{dT_p^*}{dx^*} \right] + (M^2 - 1) \frac{2C_p u^{*2}}{\gamma R T^{*2}} \left[ \frac{\kappa C_w}{C_p} \frac{dT_p^*}{dx^*} + 2\kappa u_p^* \frac{du_p^*}{dx^*} \right] \quad (26) \end{aligned}$$

$$Z = \frac{1}{2} (M^2 - 1)^2 \quad OR \quad M^2 = 1 \mp \sqrt{2Z} \quad (27 \text{ a\&b})$$

$$u^{*2} = T^* M^2 \frac{\gamma R}{2C_p} \quad (28)$$

In Equation (27 b) above, the negative sign applies when flow velocities are subsonic, and the positive sign applies for supersonic flow velocities.

Equations (13), (15), (16), (26), (27 a) and (28) are 6 equations describing the variation of 7 variables ( $u_p^*$ ,  $T_p^*$ ,  $Z$ ,  $A^*$ ,  $T^*$ ,  $u^*$  and  $M$ ) with  $x^*$ . If the nozzle profile ( $A^*(x^*)$ ) is specified, then these equations can be solved, beginning with the following boundary conditions:

$$T^* = T_p^* = 1; u^* = M = u_p^* = 0; Z = 0.5 \quad (29)$$

The integration performed with this set of equations encountered severe numerical difficulties near the location where the Mach number based on the speed of sound in gas approached unity. Several remedies, such as (1) the use of analytical jacobian in integration and (2) the use of L'Hospital's rule, were tried but the problem persisted. This approach was, consequently, abandoned, and the approach, described earlier, directly using the flow velocity  $u^*$  was utilized to obtain solutions.

## NUMERICAL SIMULATION OF NASA-KSC SUPERSONIC NOZZLE

The solution procedure for arbitrary area variations, developed and verified above, was utilized to numerically simulate the flow behavior in the NASA-KSC supersonic nozzle. These efforts and the results therefrom are presented in this section.

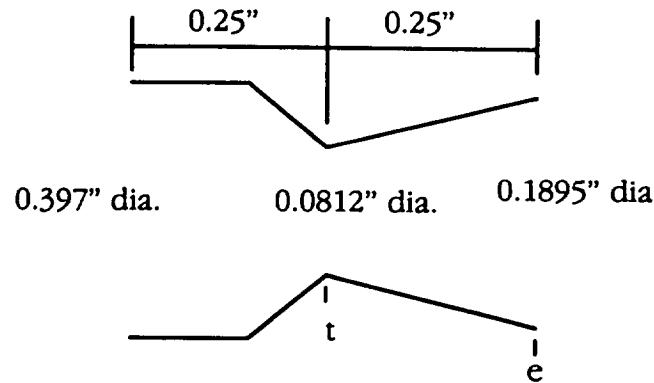


Figure 3: Schematic of NASA-KSC Nozzle

Figure 3 shows the NASA-KSC supersonic nozzle in schematic. As illustrated in, and described in connection with, Figure 1, the nozzle is supplied with a mixture of air and water. The diameter of the nozzle passage linearly decreases up to the throat, and then linearly increases. By maintaining a sufficiently high pressure upstream of the nozzle, the gas flow can be accelerated to supersonic speeds in the nozzle. It is expected that the gas would, by momentum interaction, accelerate the water droplets. Thus, under the right conditions, the exit jet from the nozzle consists of gas flow with entrained high-velocity water droplets, and may be used as a surface cleaning device that works through "impact."

The area profile of the above nozzle was used as input into the developed computer code in an effort to simulate the flow through it. Again, a guess value for  $\alpha$  was used to start the solution (recall that the guess is to be checked, and, perhaps corrected, at the throat). However, no solution could be obtained. Initially the difficulty was thought to be due to the guess value for  $\alpha$  being too far removed from its correct value. Consequently, a wide range of values for  $\alpha$  was tried. Again, no solution could be found. After some reflection, the reason for this behavior was determined to be the incompatibility between the area and the velocity information specified at the upstream end of the nozzle.

Consider a converging-diverging nozzle attached to an upstream tank. The passage area of the nozzle is initially very large (theoretically infinity at the junction between tank and nozzle). In the NASA-KSC nozzle, the diameter at nozzle entry is 0.397". This corresponds to an area ratio (area/throat area) of 23.9. The Mach number corresponding to this area ratio is about 0.02, which corresponds to a velocity of about 7 m/s. While this is small, it is not small in the "numerical sense." In carrying out the solution for the NASA-KSC nozzle, the velocity at the nozzle entry is specified to be zero, and the area ratio there is 23.9. These

two items of information are fundamentally incompatible with one another. It is this fundamental incompatibility that is responsible for the failure of the numerical method in this case. If the area variation were known from a "truly" low-velocity location, the numerical method would have been successful. Support for this statement is provided by the success of the method in obtaining the correct velocity profiles in the test cases. In each of these test cases, the area variations were known from a "truly" low-velocity location unlike in the NASA-KSC nozzle.

Due to this difficulty, the method and the associated code, described above, are not of utility in numerically simulating the flow through the NASA-KSC nozzle. Consequently, an alternate method has to be developed for this purpose. The alternate method, with the rationale behind it, is described in what follows.

Since the flow is modeled as one-dimensional, the characteristics of the flow at any nozzle location depend on the area there, and not on the actual nozzle profile used to reach that location. Consider two nozzles both with the same exit-to-throat area ratio, but which use different profiles to arrive from the throat to the exit. Within the framework of one-dimensional flow, the exit conditions from both nozzles would be the same, in spite of the different nozzle profiles utilized in them. This observation suggests a straightforward method for numerically simulating flow through a given nozzle.

In the numerical simulation, the velocity variation through the nozzle is assumed to be linear, that is  $u^*$  at a distance  $x^*$  from the nozzle entrance is assumed to be  $\alpha x^*$ . This assumed  $u^*$  variation can be used in Equations (12) through (16) to obtain closed form solutions for the other significant variables ( $u_p^*$ ,  $T_p^*$ ,  $T^*$ ,  $p^*$  and  $A^*$ ) as follows.

$$u_p^* = \beta x^* \quad (30)$$

$$T_p^* = 1 - \frac{D}{\beta} \left[ \frac{\alpha^2 + \kappa \beta^2}{\kappa C_w} \right] x^{*2} \quad (31)$$

$$\frac{D}{\beta} \left( 1 + \frac{1}{C_p} \right) + 2$$

$$T^* = 1 - \alpha^2 x^{*2} \frac{C_p}{C_{eq}} \quad (32)$$

$$p^* = \left( 1 - \alpha^2 x^{*2} \frac{C_p}{C_{eq}} \right)^{\frac{C_{eq}}{\kappa} [1 + \kappa \frac{\beta^2}{\alpha^2}]} \quad (33)$$

$$A^* = \frac{1}{\alpha x^* \left( 1 - \alpha^2 x^{*2} \frac{C_p}{C_{eq}} \right)^{\frac{C_{eq}}{\kappa} (1 + \kappa \frac{\beta^2}{\alpha^2})}} \quad (34)$$

where  $\beta$  and  $C_{eq}$  are given by Equations 24 and 25, respectively. Thus, it is possible to determine the variation of  $u^*$ ,  $u_p^*$ ,  $T_p^*$ ,  $T^*$ ,  $p^*$  and  $A^*$  with location  $x^*$  along the nozzle. These equations form the basis for a code that has been developed in FORTRAN for the numerical simulation of the supersonic nozzle. The code is named ssl.f.

In performing the calculations, the actual value chosen for  $\alpha$  has no effect on the flow properties at a given area ratio location. In fact, the program user may convince himself of this behavior by running the code for two different values of  $\alpha$ . Comparison of the results would show that the flow properties at locations with the same area ratios would be the same for the two cases. *However, the  $x^*$  locations for attainment of a given area ratio would not be the same in the two cases.* A larger  $\alpha$  would simulate a nozzle with more rapid acceleration than a smaller  $\alpha$ , and thus would have a more rapidly varying area ratio with distance. Consequently, a given area ratio would be attained at a smaller  $x^*$  in a larger  $\alpha$  nozzle than in a smaller  $\alpha$  nozzle.

A study of the equations and the program will reveal that the results are independent of the pressure upstream of the nozzle. Specifically, the method assumes that the nozzle expands the flow to supersonic speeds, regardless of the pressure upstream of the nozzle. This is simply a result of the physical phenomenon that, once the upstream pressure is large enough to establish supersonic flow through the entire nozzle, the flow becomes independent of the upstream pressure, and depends only on the nozzle area ratio. Thus, there exists a critical pressure above which the nozzle solution becomes independent of the upstream pressure, and supersonic flow would always be maintained. A tacit assumption made in the present development is that the code will be exercised only above this critical pressure. This is a reasonable assumption to make since below the critical pressure, shocks enter the nozzle, and the resulting flow is not expected to be effective in cleaning due to the drop in flow velocities across shocks.

The above-mentioned critical pressure is a function of the area ratio of the nozzle used. The critical pressure determination for a given area ratio nozzle is a straightforward problem in gas dynamics. A FORTRAN computer code named pcrit.f has been developed for this purpose, and accompanies the report. The code requires as input the value of the nozzle area ratio, and provides as output the minimum suggested pressure upstream of the nozzle.

In the interest of completeness, a related problem should also be addressed at this point. Just as a minimum pressure exists for a given area-ratio nozzle, there exists a threshold area ratio that must not be exceeded for a given upstream pressure. If this area ratio is exceeded, shocks again would enter the nozzle. For operating pressures currently in use with the cleaning system (around 300 psig), this area ratio is very large, and need not be cause for concern. However, another computer code named acrit.f has been developed for determining this maximum area ratio. The program requires as input the upstream pressure, and provides the threshold area ratio on output.

## PARAMETRIC STUDIES WITH THE NASA-KSC NOZZLE

The developed computer code was used to perform very limited parametric studies. It would have been desirable to carry out extensive investigations with the developed model. However, partly due to the short duration of the project, and partly due to the time consumed in developing the model, parametric studies were restricted to the two cases for which experimental comparisons were available.

Accordingly, the NASA-KSC nozzle was chosen as the candidate for the parametric studies. It was 0.5" long, and had throat- and exit-section diameters of 0.0812" and 0.1895", respectively. Air and water were fed into the nozzle from upstream tanks. The various controlling variables were chosen to be the same as those used in the experiments. The experiments were performed by Dr. Sunil David of BCC, and the reader is referred to Dr. David's report for details of the experimental setup and measurements. As mentioned earlier, two experimental conditions were chosen for comparison with the model. In the first, the pressure upstream of the nozzle was 320 psig, and the air supply tank was at a temperature of 11°C. The water flow rate in this experiment was 0.0519 liters/min (4 liters in 77 minutes). In the second, the pressure upstream of the nozzle was 420 psig. The air tank temperature was again 11°C. The water flow rate into the nozzle was 0.056 liters/min (5 liters in 90 minutes). The water flow rates in both cases provided very small particle-to gas mass loading ( $\alpha$  of 0.0312 in the first case and 0.0474 in the second). These values were input into the developed code to determine the nozzle flow characteristics. Of particular interest were the gas velocities at the nozzle exit. In constructing the solution,  $\alpha$  was assumed to be 0.87 in both these cases.

In addition, air was assumed to have a coefficient of viscosity  $\mu$  of  $1.7894 (10^{-5})$  kg/m/s and a coefficient of thermal conductivity of  $2.4335 (10^{-6})$  J/m/s/K. The specific heats of air and water were taken to be 1004.5 J/kg-K and 4184 J/kg-K, respectively. The density of water was assumed to be 1000 kg/m<sup>3</sup>. Water droplets were assumed to be spherical, and each water droplet was assumed to have a diameter of 2.5 microns. Based on these assumed properties, the nondimensional coefficients C and D, defined in equations (17 a&b) were determined to be 0.87 and  $1.88(10^{-5})$ , respectively.

Results from the code are presented in Figures 4 and 5. Figure 4 corresponds to the first case, and Figure 5 to the second. In each of these Figures is shown the value of  $x^*$  where the area ratio is equal to the exit-to-throat area ratio of the NASA-KSC nozzle. Thus, the computed values of velocities at these locations should compare with the exit velocities from the NASA-KSC nozzle. In both cases, the computed air velocity is 670 m/s. The independence of the nozzle exit conditions to upstream pressure has been explained elsewhere in the report. The measured values are about the same, at 630 m/s, see Dr. David's report, for the two cases. Considering the simplicity of the model, the excellent agreement between the model and experimental values is noteworthy.

It can also be seen from the Figures that the air temperature rapidly drops through the nozzle in both cases. In contrast, the particle-phase temperature remains constant at its upstream value all through the nozzle. This result seems to be supported by experimental observations: Dr David has observed that the droplets issuing from the nozzle



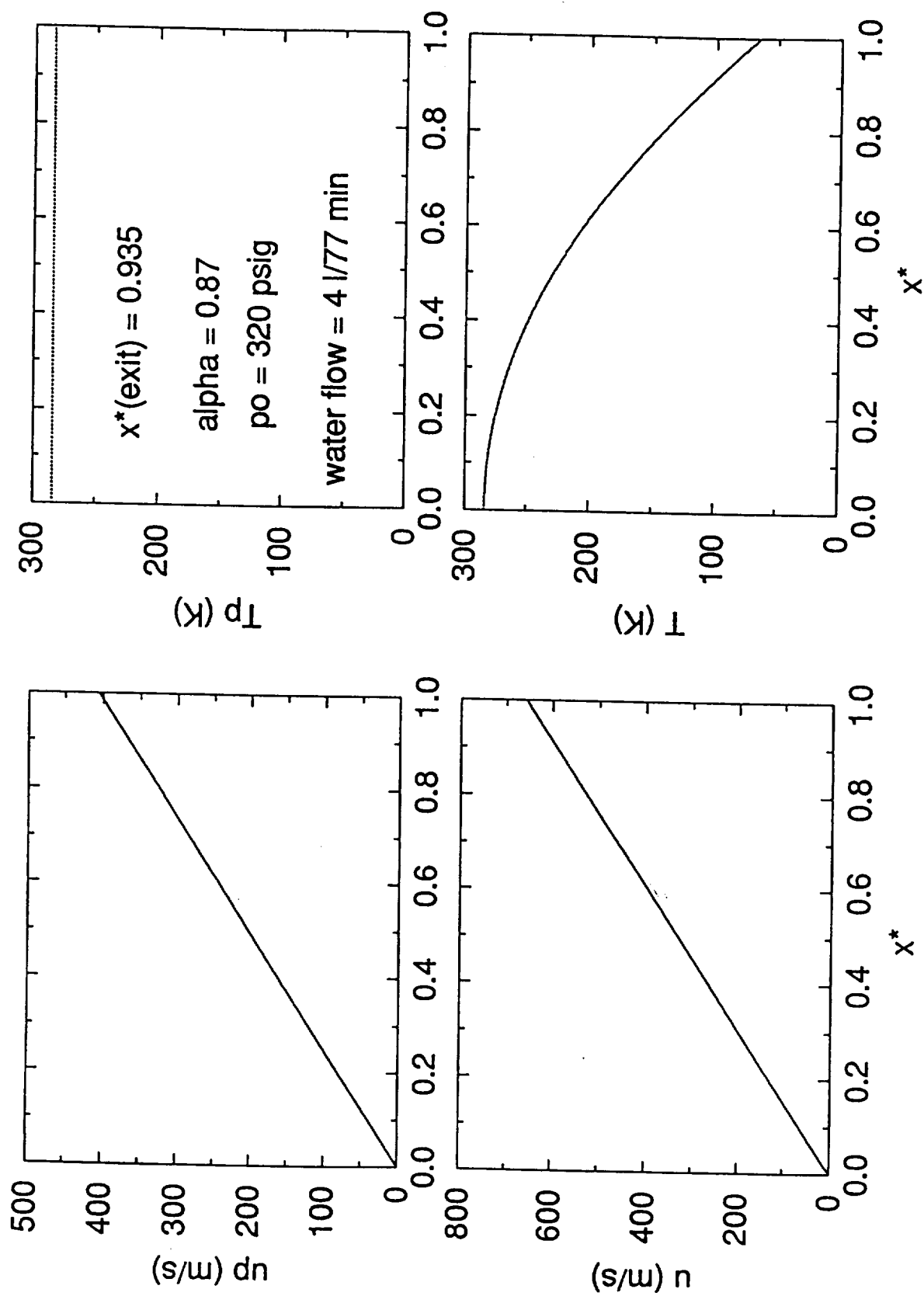


Figure 4: Numerical Solution for Case 1

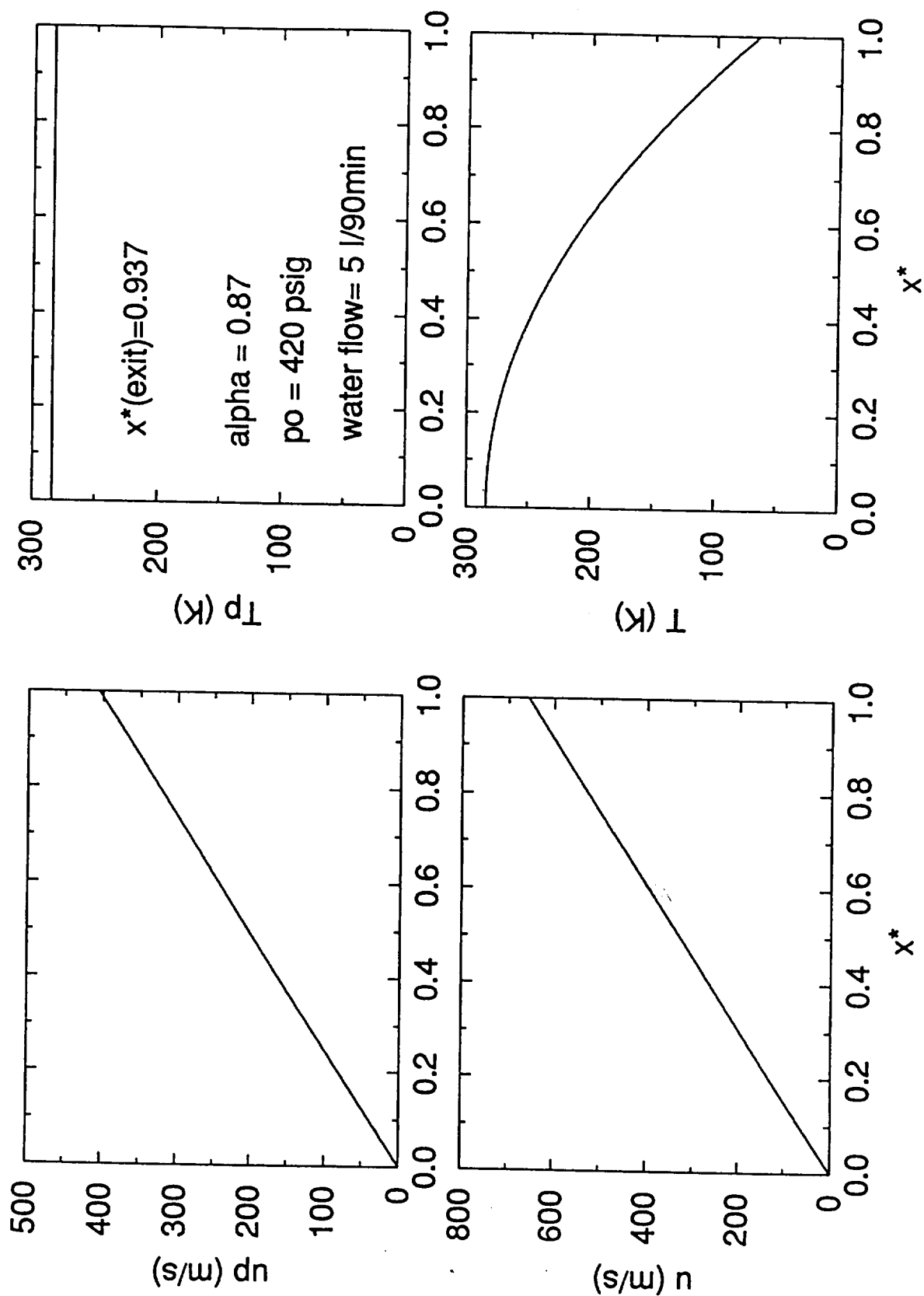


Figure 5: Numerical Solution for Case 2

are in liquid form, suggesting that they are at temperatures above 0°C. This result suggests that the initial model of Caimi and Thaxton<sup>2</sup> may not properly describe the nozzle flow, as explained below.

In their development, Caimi and Thaxton<sup>2</sup> assumed thermal equilibrium (due to rapid heat transfer) between the two phases. Results of the current investigation would suggest that the assumption of no heat transfer between the phases would be much closer to reality than that of rapid heat transfer.

## CONCLUSIONS

This project was concerned with the investigation of a supersonic gas-liquid cleaning system. The work consisted of an experimental study of the flow of air-water mixture through a nozzle. This experimental work was supplemented by the development of a theoretical model capable of simulating the nozzle flow. Bethune Cookman College conducted the experimental part of the study, and ERAU conducted the theoretical part.

The work has resulted in the successful development of a theoretical nozzle flow model. The associated computer code named `ssl.f` is provided with this report. It is easy to use, and there is a good possibility that it can be executed on a personal computer. In addition, two other codes `pcrit.f` and `acrit.f` have been included. The need for, and the use of, these codes have been explained in the report. Both of these codes utilize a nonlinear algebraic equation solver from the IMSL library. If the host computer does not have IMSL, then it would not be possible to recompile these two source codes to generate the required executables. To overcome this problem, in addition to the source program, the executables are also being supplied with this report.

There are two diskettes attached. Each of these diskettes contains the same files; namely, `ssl.f`, `pcrit.f`, `acrit.f`, `ssle`, `pcrite` and `acrite`. `ssl.f`, `pcrit.f` and `acrit.f` are source codes, and `ssle`, `pcrite` and `acrite` are associated executables. One diskette contains the files in UNIX format, and the other in DOS format. The DOS-format diskette contains the six files, stored in succession. In the UNIX-format, the files have been gathered into a master tape archive file called 'exe'. This master archive contains two files, one named 'exe' and the other named 'source'. File 'exe' contains the executable files, and file 'source' contains the source codes. The following procedures may be used to retrieve and use these files in a UNIX-driven workstation.

### RETRIVING FILES FROM DISKETTE ONTO COMPUTER

- (1) Create a directory called nasa: **`mkdir nasa`**
- (2) Make 'pulse' the working directory: **`cd nasa`**
- (3) Extract file 'exe' and 'source' from diskette: **`tar xvf /dev/rfd0 exe source`**. There should now be two files named 'exe' and 'source' in the working directory.
- (4) Extract files 'ssl.f', 'pcrit.f' and 'acrit.f' from 'source': **`ar x source`**. The three source files should now be in the directory.
- (5) Extract files 'ssle', 'pcrite' and 'acrite' from 'exe': **`ar x exe`**. The three executables should now be in the directory.

### COMPILING AND LINKING TO CREATE EXECUTABLES

- (1) Compile 'ssl.f' and store object code in 'ssl.o': **`f77 -c ssl.f`**
- (2) Compile 'pcrit.f' and store object code in 'pcrit.o': **`f77 -c pcrit.f`**
- (3) Compile 'acrit.f' and store object code in 'acrit.o': **`f77 -c acrit.f`**
- (4) Link to create executable 'ssle': **`f77 -o ssle ssl.o`**
- (5) Link to create executable 'pcrite': **`f77 -o pcrite pcrit.o 'path'/libimsl.a`**. As mentioned

elsewhere, 'pcrit.f' utilizes the IMSL library for solving a nonlinear equation that arises in the problem. Thus, if IMSL is not available in the host computer, this command would not work. If IMSL does reside in the host computer, the path leading to the directory holding the IMSL library is to be used in place of 'path' in the command.

(6) Link to create executable 'acrite': **f77 -o acrite acrit.o 'path'/libimsl.a**. Again, since this program uses IMSL, comments made in reference to creating 'pcrite' apply here as well.

### EXECUTING CODES

- (1) To run 'ssle': **ssle**. Execution creates two output files 'out1.dat' and 'out2.dat'.
- (2) To run 'pcrite': **pcrite**. Results are displayed on screen.
- (3) To run 'acrite': **acrite**. Results are displayed on screen.

Continuing with the concluding remarks, the nozzle model was exercised at the same conditions for which experimental data were obtained in order to determine its validity. It was found that the model correctly predicted the experimental behavior at the two conditions checked. The results also pointed out that the assumption, as made in Reference 2, of thermal equilibrium between the two phases may not be valid.

It would have been desirable to conduct extensive parametric studies with the model. Time constraints did not permit such studies. Time constraints limited the scope of the experimental investigation as well. To more fully characterize the nozzle and its capability as a cleaning tool, ERAU may continue to work on this problem in the coming months. The work, if pursued, will likely employ the services of a Masters-level student providing good educational experience to the student on a project of considerable current interest.

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# **SUPERSONIC GAS-LIQUID CLEANING SYSTEM**

## **FINAL PROJECT REPORT**

**MARCH 22, 1995**

This project status report is submitted by Precision Fabricating and Cleaning Co., Inc. (PFC) to Bethune-Cookman College (B-CC), and summarizes work performed between September 12, 1994 and March 11, 1995 in support of this research project (Ref. TRDA Grant # 411).

This Supersonic Gas-Liquid Cleaning System research project came about in support of NASA's technology transfer program. This approach to uniting NASA technology with local manufacturing reflects NASA's involvement in programs and projects that are mutually beneficial to the parties involved.

The development of this Supersonic Gas-Liquid Cleaning System came about in response to the mandatory elimination of CFC's from cleaning operations. The CFC's used in these operations were deemed to be environmentally hazardous and therefore alternative methods of cleaning and subsequent validation of cleaned items were required. NASA engineers developed this nozzle system as one alternative method of cleaning and validation. In fact, it's use has already been approved in NASA KSC's cleaning specification KSC-C-123G, "Surface Cleanliness of Fluid Systems, Specification for", dated August 4, 1994.

Even though it's use was already approved in KSC-C-123G, the supersonic nozzle system still required a characterization study to verify the engineer's claims of "supersonic" properties. Theoretically these supersonic properties exist but thus far no empirical data had been gathered to substantiate these claims. Therefore one objective of the characterization study was to provide empirical verification of the theoretical design. In addition, only one nozzle configuration had ever been fabricated. Any information about two-phase flow through a nozzle that could improve the design of future nozzles was certainly desirable.

A second objective of the study was to determine an optimal geometric design of the nozzle for use in cleaning operations currently taking place at Kennedy Space Center. Whatever the application of the nozzle, its optimal design should call for the water droplets to possess the maximum velocity practically possible. That way the kinetic energy used for cleaning will come from the velocity of the droplets and will not be so dependent upon the mass of the droplets. The current nozzle configuration uses approximately one quart of water per one-half hour of operation at 300 psig. The optimal operating range for cleaning surfaces is currently approximately two inches (axially) from the exit plane of the nozzle.

A third objective of this phase of the project was the development of a computer model in which system parameters could be varied to determine different optimal designs depending on application criteria. Inherent to this characterization study was the requirement for a literature search to locate any information that described current surface cleaning methods, information that would be of assistance in the optimization of nozzle designs, as well as any computer modeling that might have already been completed regarding two-phase flow through a nozzle.

The accomplishment of the above mentioned three project objectives required the participation of several parties. Bethune-Cookman College (B-CC) and Embry-Riddle Aeronautical University (ERAU) provided support with analytical verification, mathematical modeling, as well as experiment design. Precision Fabricating and Cleaning Company, Inc. (PFC) provided testing facilities, manpower, and system components to facilitate testing of a second nozzle system. NASA Kennedy Space Center (KSC) fabricated and supplied the actual second nozzle and water injector assembly required for this second nozzle system. NASA's Langley Research Center (LARC) supplied facilities and manpower to support final stages of nozzle testing.

First the nozzle testing procedures and equipment requirements were discussed and decided upon by doctorate professors from Bethune-Cookman College and Embry-Riddle Aeronautical University. Analytical verification of the existing prototype nozzle system was carried out by ERAU. This involved verifying the equations, calculations, and investigating any assumptions made by the NASA design engineers. Also investigated was the feasibility of applying basic gas flow equations to two-phase flows.

Once the testing procedures and equipment requirements were decided upon, efforts were made by both NASA and PFC to locate, obtain, and setup this equipment. PFC transformed their Mobile Clean Room into a supersonic nozzle testing facility to support these parametric studies. PFC fabricated and assembled a regulated supply system including regulator panels, water supply system, supply hoses, nozzle support stands, etc. B-CC supplied additional necessary equipment including lasers and optical benches. As stated above, NASA KSC supplied the nozzle and water injector assembly.

Measurements were taken over several days to obtain data describing the velocity profile of the nozzle using Breathing Air only. This was accomplished through the use of a hot-film probe, laser, and optical bench. The hot-film probe worked quite well, providing data that was consistent, repeatable and as theoretically predicted. Using the calibration curve supplied by the probe manufacturer, the actual exit velocities could be calculated. The laser was used to maintain axial alignment of the probe with the nozzle. Measurements were taken over a range of pressures from 200 psig to 500 psig. Readings were taken beginning at the exit plane of the nozzle and incrementally increased out to a distance of 10 inches away (axially) from the exit plane.

During this phase of testing, observations of the flow characteristics of the nozzle clearly showed shock waves exiting the nozzle. Several black and white photographs were taken of these shock waves. The data gathered was analyzed and incorporated into the mathematical model as applicable.

The next phase of testing involved introducing water droplets into the gas stream. This was accomplished through the use of the NASA KSC designed injector assembly. This injector regulated the amount of water introduced into the system by means of a 0.0125 inch orifice. System differential pressure of 20 psig forced the water through the orifice and into the gas stream. During initial setup and configuration of this gas-liquid phase of testing the hot-film probe was inadvertently destroyed. The probe was determined to be irreparable and efforts were undertaken to devise alternative methods of data acquisition.

Several different data acquisition methods were discussed between all parties involved. The use of a Laser Doppler Velocimeter (LDV) was brought up as a viable approach to obtaining data on the gas-liquid system. The LDV has the capability to provide the desired information but it is an expensive piece of equipment that is not easily transported. High-speed photography (1,000,000 frames per second) was presented as a possible method of obtaining particle size and particle distribution data. Attempts have already been made by NASA to use such high-speed photography in the past, however with the optics package that was available at the time, satisfactory results could not be obtained. In addition, the photographic equipment and facilities could not be obtained within the short time frame of this project. Possibly with a different optics package, this will prove to be a viable method of data acquisition in the future.

It was determined that a pitot tube probe could be used to measure the desired velocity data. The pitot tube has the ability to withstand the detrimental effects of the liquid droplets in the system. The only drawback to the pitot tube probe is that it is somewhat intrusive to the flow being measured.

Efforts were made to locate and obtain a supersonic pitot tube probe. These efforts were unsuccessful. Therefore, with joint effort from both B-CC and PFC a suitable pitot tube probe was fabricated. The probe was a blunt end probe fabricated from a hypodermic needle and one-eighth inch copper tubing. This probe was coupled to a pressure transducer with strip chart recorder provided by NASA.

The pitot tube probe was successfully used to measure velocities axially from the exit plane to 10 inches away. First the probe was used to obtain velocity data using only Breathing Air (no water). This data corresponded with the "gas only" data gathered using the hot-film probe earlier. Next the water droplets were introduced into the system as described above and testing continued. Again, measurements were taken over a range of pressures from 200 psig to 500 psig and from 0 to 10 inches away from the exit plane of the nozzle. The data gathered using the pitot tube probe was quite repeatable and as expected.

The flow characteristics of the nozzle with the gas-liquid mixture were observed during this second phase of testing. As before with gas only, shock waves were visible exiting the nozzle. These shock waves were again photographed using black and white film.

All the data obtained from testing performed at PFC was analyzed by B-CC and ERAU. This data was incorporated into the mathematical model of the nozzle developed by ERAU. The model was "fine tuned" using this empirical data to insure that it did indeed correctly represent the existing nozzle configuration.

Arrangements were made through LARC to use Laser Doppler Anemometry as another method to verify the two-phase flow data obtained with the pitot tube probe. The equipment required to perform such testing was located at NASA's Langley Research Center. The Laser Doppler Anemometer (LDA) would be able to measure velocities of the gas-liquid stream exiting the nozzle without being intrusive to the flow. It was also thought that the LDA would be able to provide information on the size of the water droplets and well as the distribution of these water droplets.

Members from KSC and B-CC traveled to LARC to discuss this third phase of testing using the LDA. After the testing procedures and requirements were agreed upon, plans were made to conduct the testing. Members from both KSC and B-CC traveled to LARC to perform the testing.

The Laser Doppler Anemometer provided information on the velocity of the gas-liquid stream at the desired locations along the axis of the nozzle. Team members were unable to obtain information regarding the size of the water droplets or the distribution of these water droplets. Even so the personnel on-site at LARC were of great assistance to us throughout this testing, often at great personal sacrifice to their schedules. The velocity data obtained at LARC was analyzed by B-CC and ERAU and incorporated into the computer model as applicable.

With the completion of the testing performed at LARC, the first objective of this project was met. There now existed empirical verification of the theoretical design. The next step of the project was to determine a theoretical optimal nozzle design using the mathematical model. Unfortunately, acquiring testing equipment for use at PFC and arranging to use LARC's Laser Doppler Anemometry equipment on-site proved to be logistically difficult. This led to several schedule delays and due to the short window of the project made it necessary to revise the project requirements.

The revision of the project requirements was discussed at the last status meeting. Since the time allocated for the project was used up, it was decided that several items would be deleted from the Statement of Work. Items deleted include the requirement to refine the nozzle to its optimal configuration. Associated with this deletion is the requirement to fabricate and test any such newly designed nozzle configuration. Additionally it was desired to use the computer model to determine several possible nozzle configurations that were dependent upon the specific application of the nozzle. This information would be coupled with a market study and commercialization plan with hopes to eventually market nozzle configurations/packages that proved feasible. These requirements were also deleted from this Statement of Work.

Even though several requirements had to be deleted from the Statement of Work, the project was still a success. The objective of obtaining empirical verification of the theoretical design was met. The data showed that the water droplets did indeed exit with supersonic velocities. The development of a mathematical computer model representing the existing nozzle system was also accomplished. Although outside the scope of this current project, this computer model can still be utilized to determine several different nozzle geometry's once the system parameters pertaining to each specific application are identified.

Once the computer model is available from ERAU, PFC plans to use it to investigate the feasibility of commercializing this nozzle technology. Initially, PFC hoped this characterization study would determine two things. First, what is the lowest supply pressure that will still provide supersonic exit velocities using the current nozzle design? Second, what is the smallest geometric configuration that will provide satisfactory cleaning ability? These questions were never answered during this study and therefore PFC will pursue these issues privately. The supply pressure issue is of concern to PFC because we feel that the required 300 psig could pose safety concerns if the nozzle were to be used in commercial applications. Also, greater design flexibility can be enjoyed with smaller overall nozzle dimensions.

If the computer model shows that it is theoretically possible to achieve the desired performance from these different nozzle configurations, then PFC will look into the fabrication and empirical verification of such nozzles. So far this study has been limited to the testing of a mixture of Breathing Air and demineralized water. Theoretical and empirical studies encompassing a variety of gas/liquid mixtures and system pressures would need to be conducted to verify nozzle performance once potential applications utilizing these different mixtures were identified.

Once an application is shown to be technically feasible, a market study would be conducted to ascertain the need for such a product. If the market showed promise, a marketable "product" pertaining to that particular application would be developed. This "product" might range from developing and supplying a specific nozzle design per customer requirements, to developing, fabricating, assembling, and packaging a complete, self-contained, ready-to-use "nozzle system." The nozzle could also be incorporated as part of a larger cleaning process.

Initial applications of interest to PFC involve the precision cleaning of K-bottle and similar cylinders, as well as utilizing the nozzle's cleaning abilities in the electronics industry. PFC understands that a NASA designed K-bottle cleaner, incorporating the supersonic nozzle, already exists but as of yet PFC has not been able to perform any testing using this device as it has not been made available. PFC has already begun to compile a database of potential customers interested in using this type of nozzle technology in various commercial applications.

PFC believes that several publications should come out of this characterization study. The literature surveys performed by B-CC and ERAU could be published in literature survey journals. Articles written by B-CC and ERAU to specifically describe their aspects of this study could be published in the appropriate technical journals. Articles written by PFC pertaining to the use of this nozzle technology in the cleaning industry could be published in the appropriate trade publications, such as "Precision Cleaning" magazine.